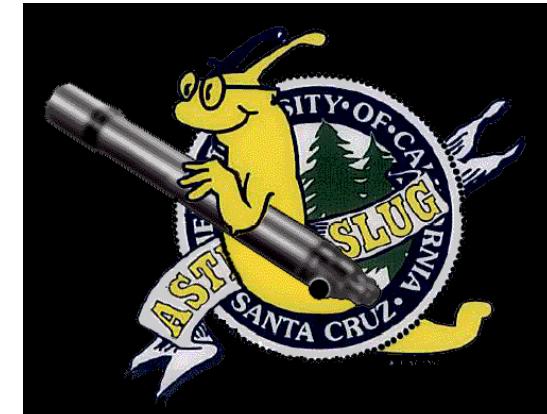


Ubiquity of Planets & Diversity of Planetary Systems: Origin & Destiny of gas giants & super Earths

Douglas N.C. Lin

Dept of Astronomy & Astrophysics, UC Santa Cruz
Kavli Institute for Astronomy & Astrophysics, Peking University

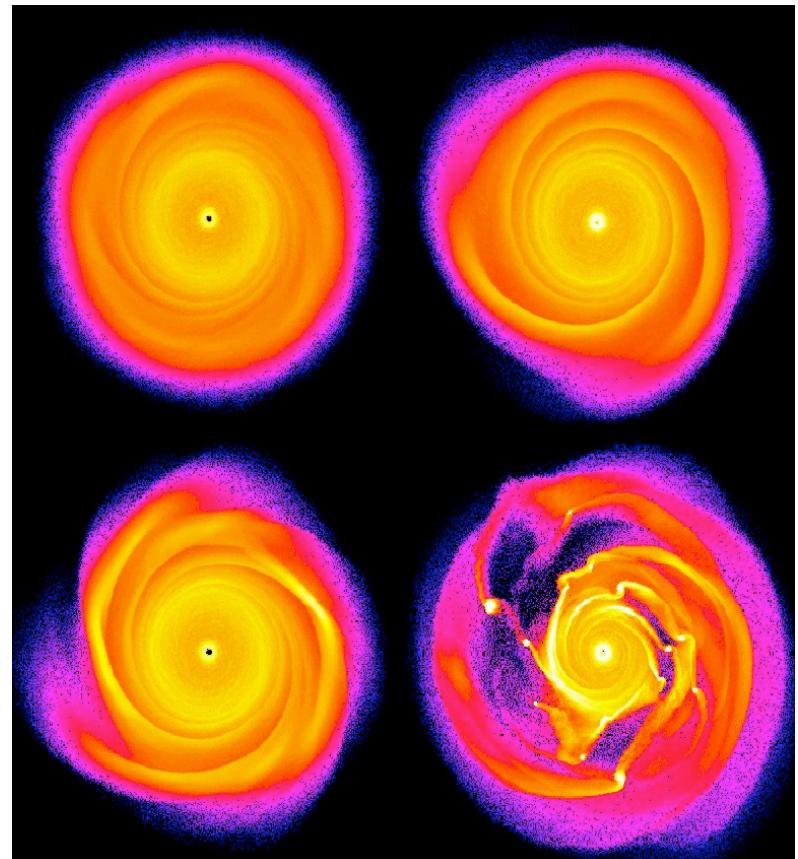
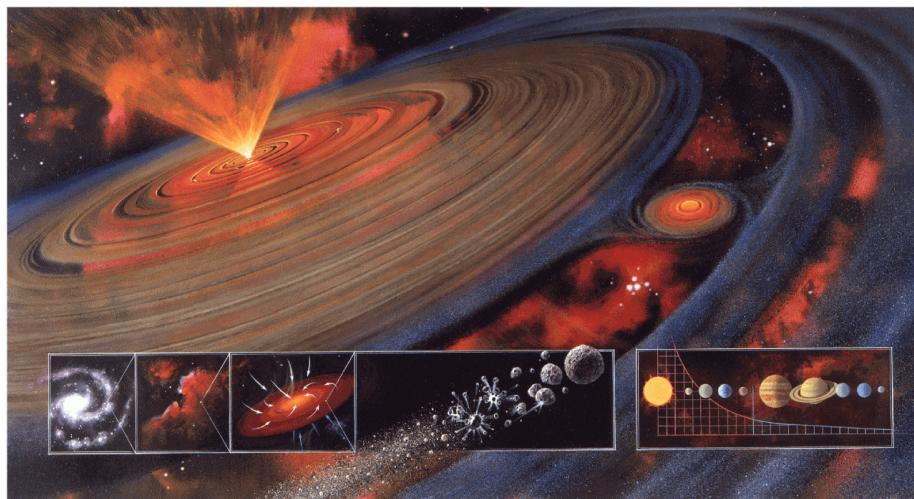
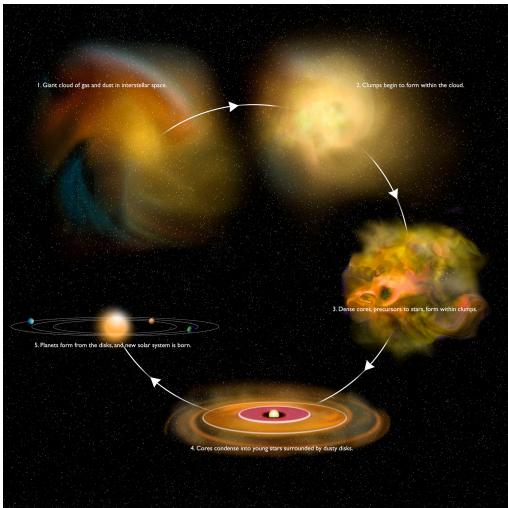
ExoPAG 7, Long Beach 1.6.2013



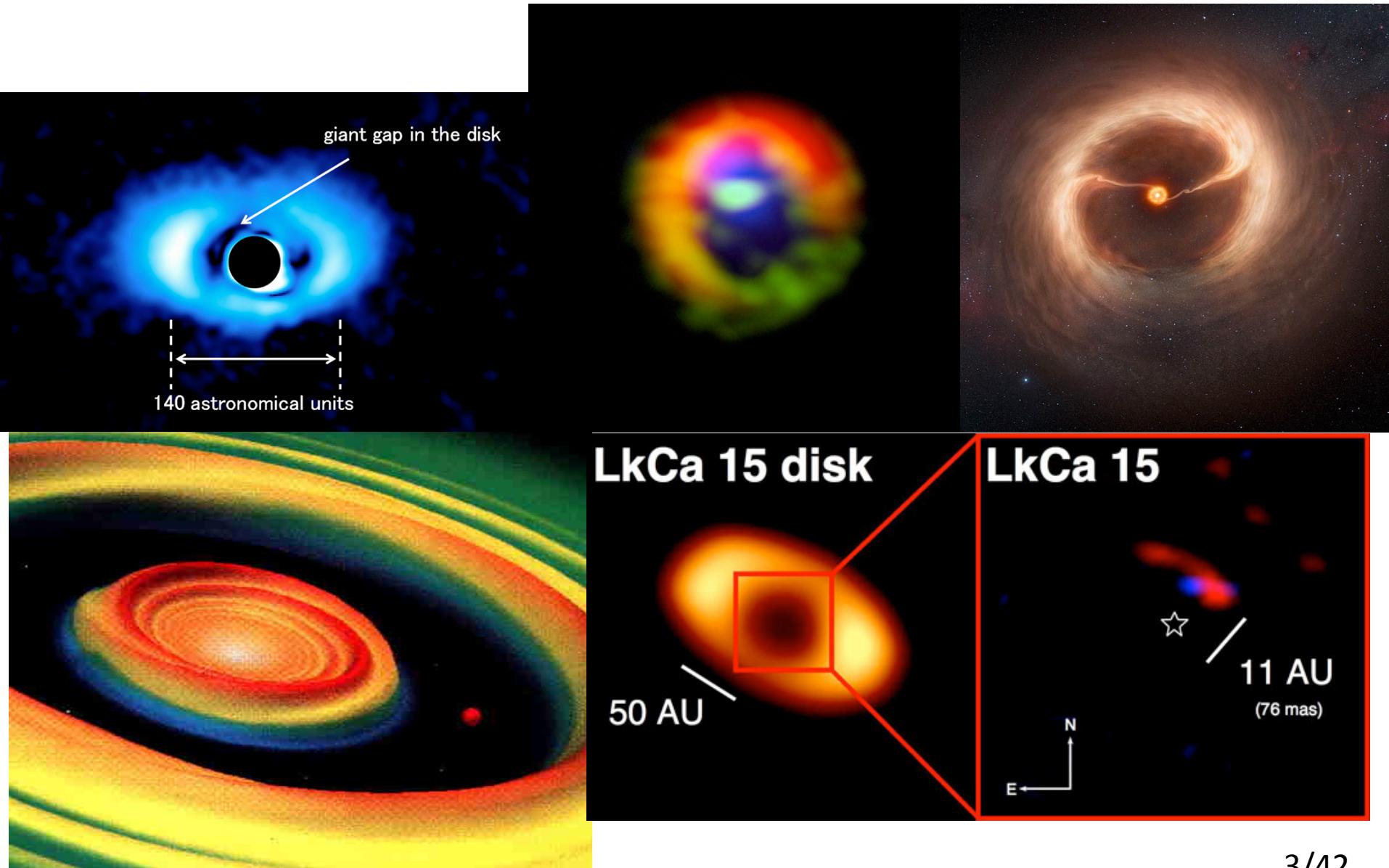
42 slides

Gas giants: some key issues

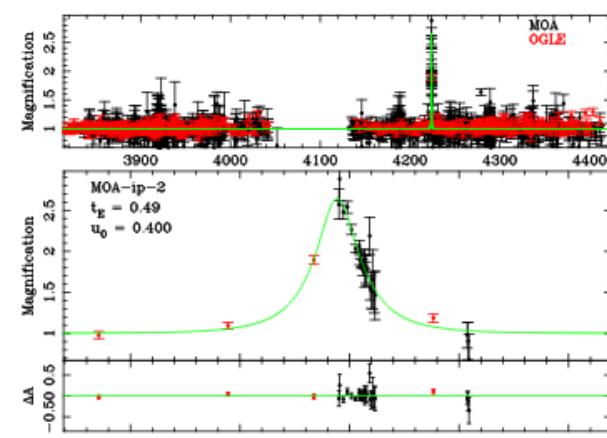
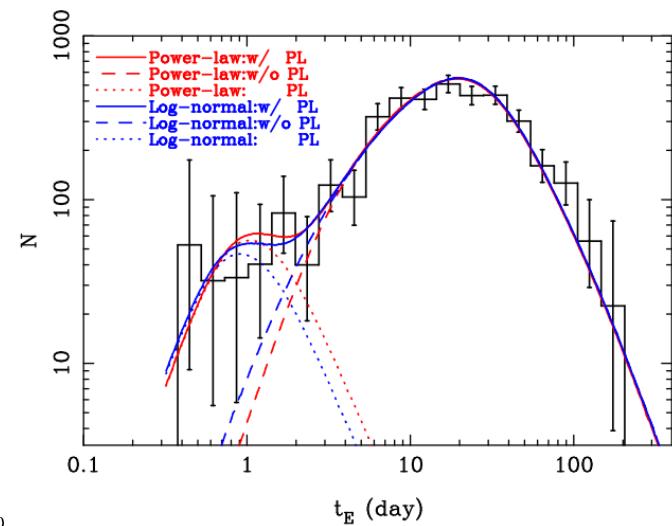
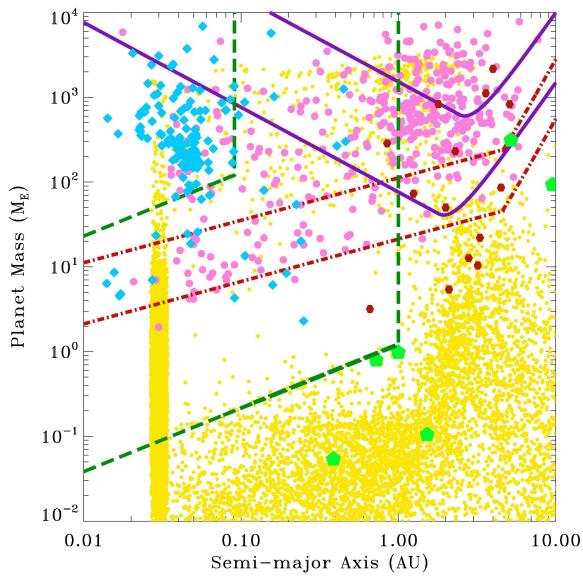
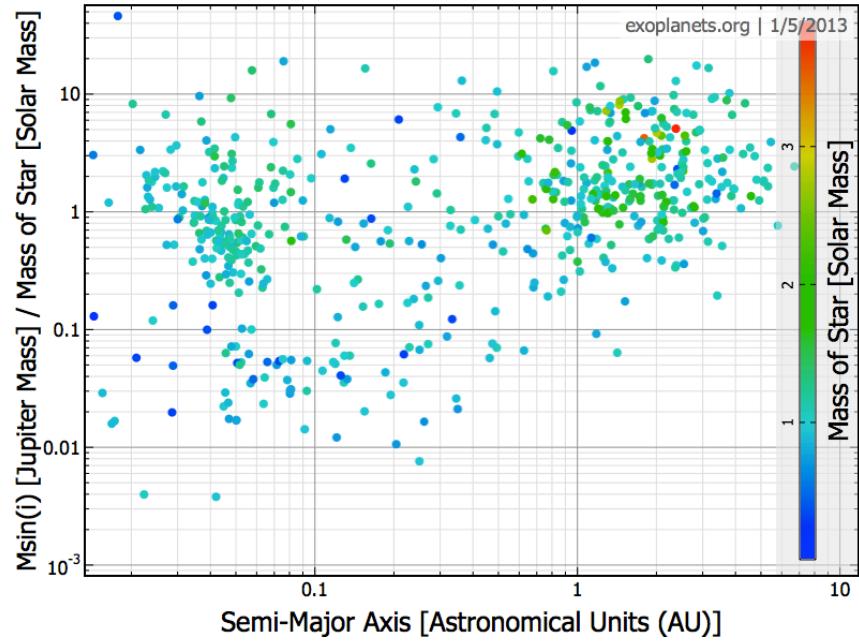
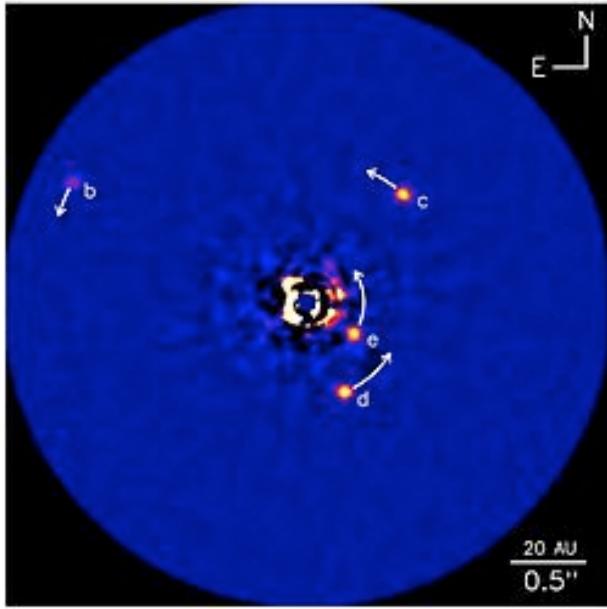
- Did most gas giant form through **core accretion** or **gravitational instability**?



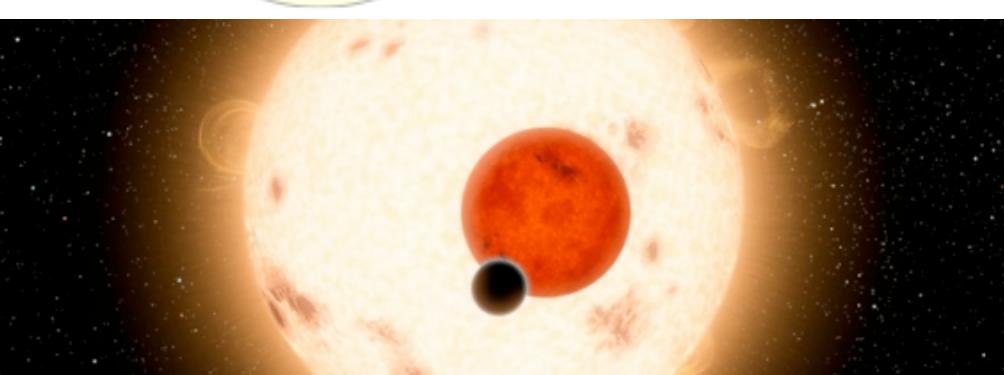
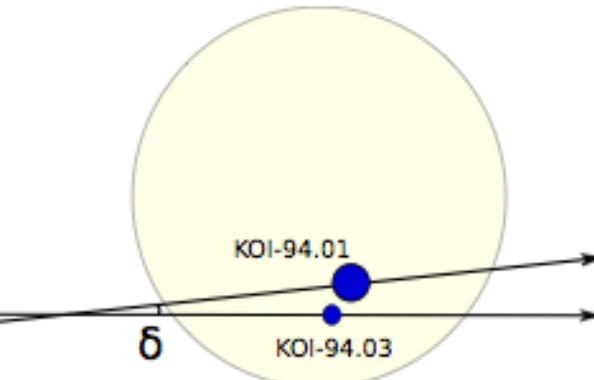
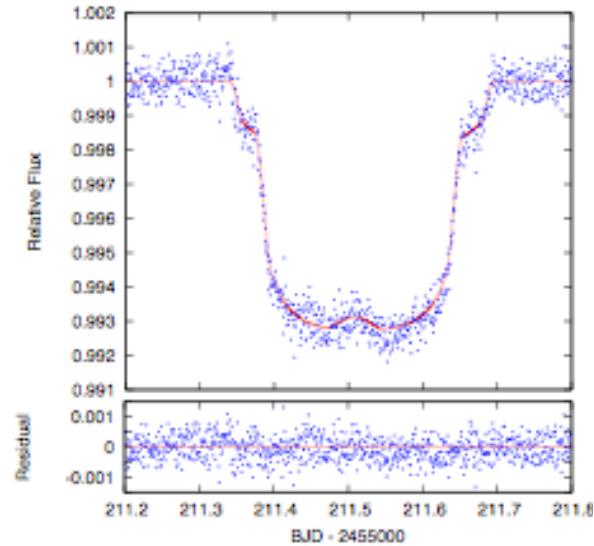
Spirals and gaps in protostellar disks



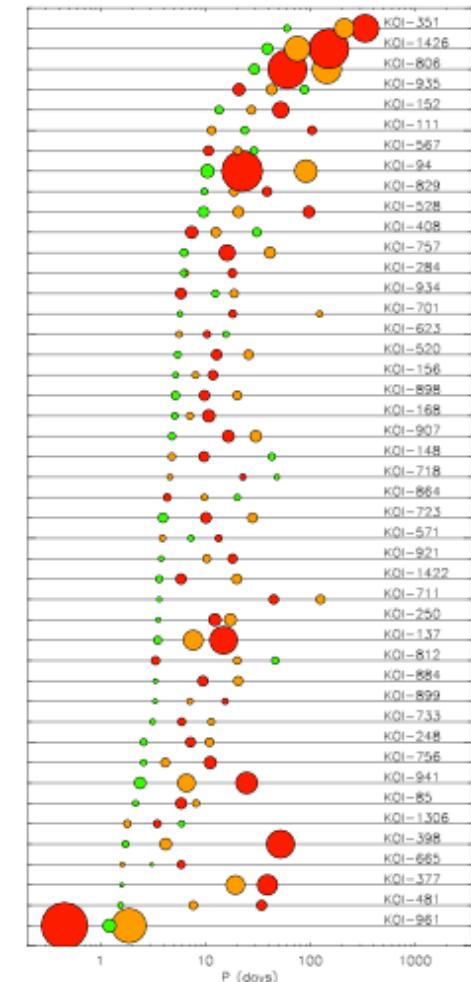
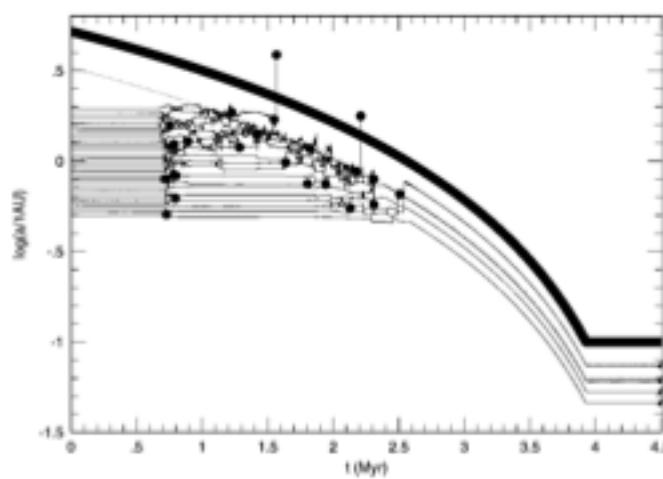
Long-period massive planets



Smoking gun for core accretion (KOI 94)

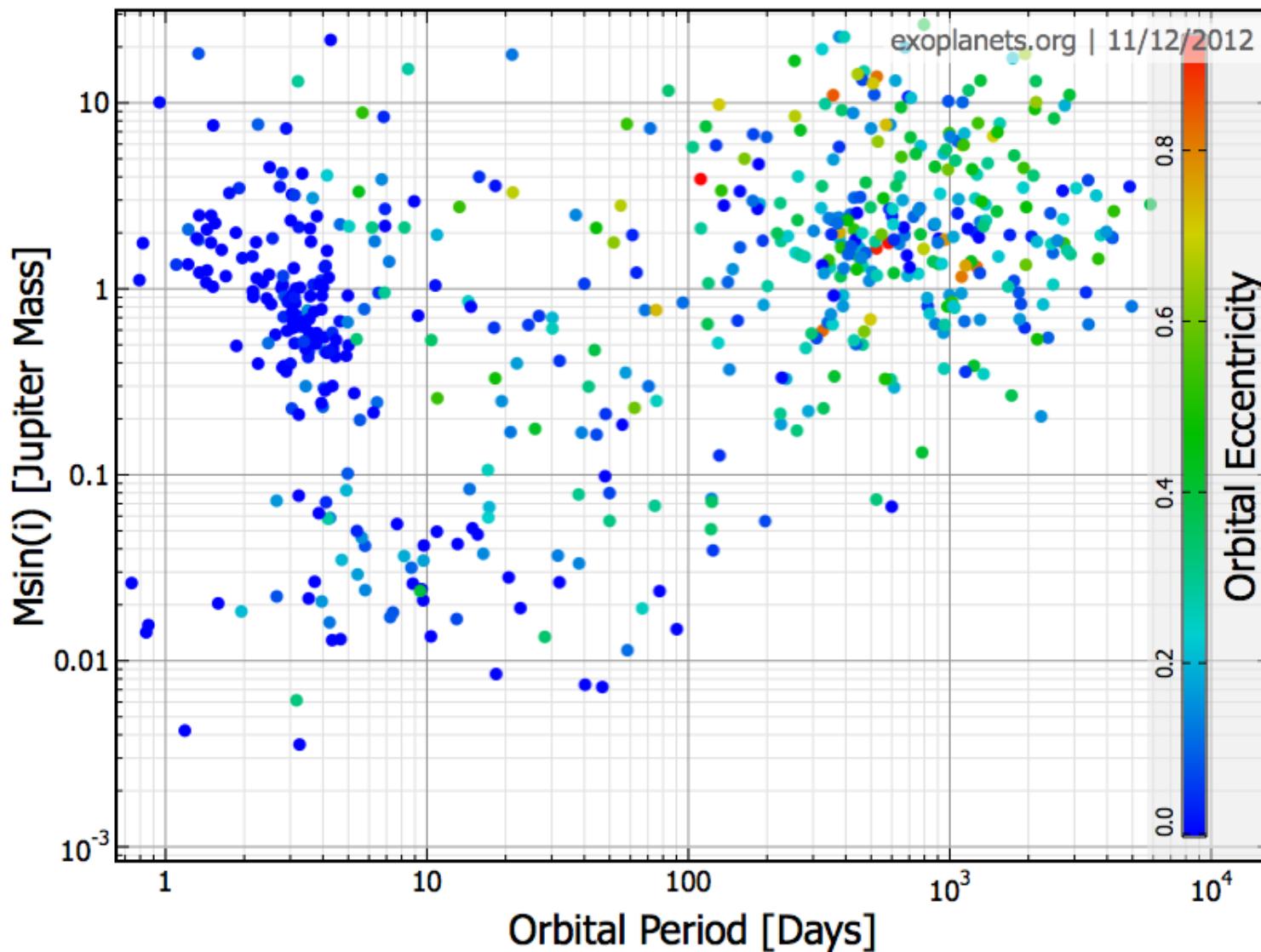


Candidate	Orbital Period (days)	R_p/R_s
KOI-94.01	22.343000 ± 0.000011	0.06856 ± 0.00012
94.02	10.423707 ± 0.000026	0.02544 ± 0.00012
94.03	54.31993 ± 0.00012	0.04058 ± 0.00013
94.04	3.743245 ± 0.000031	0.01045 ± 0.00019



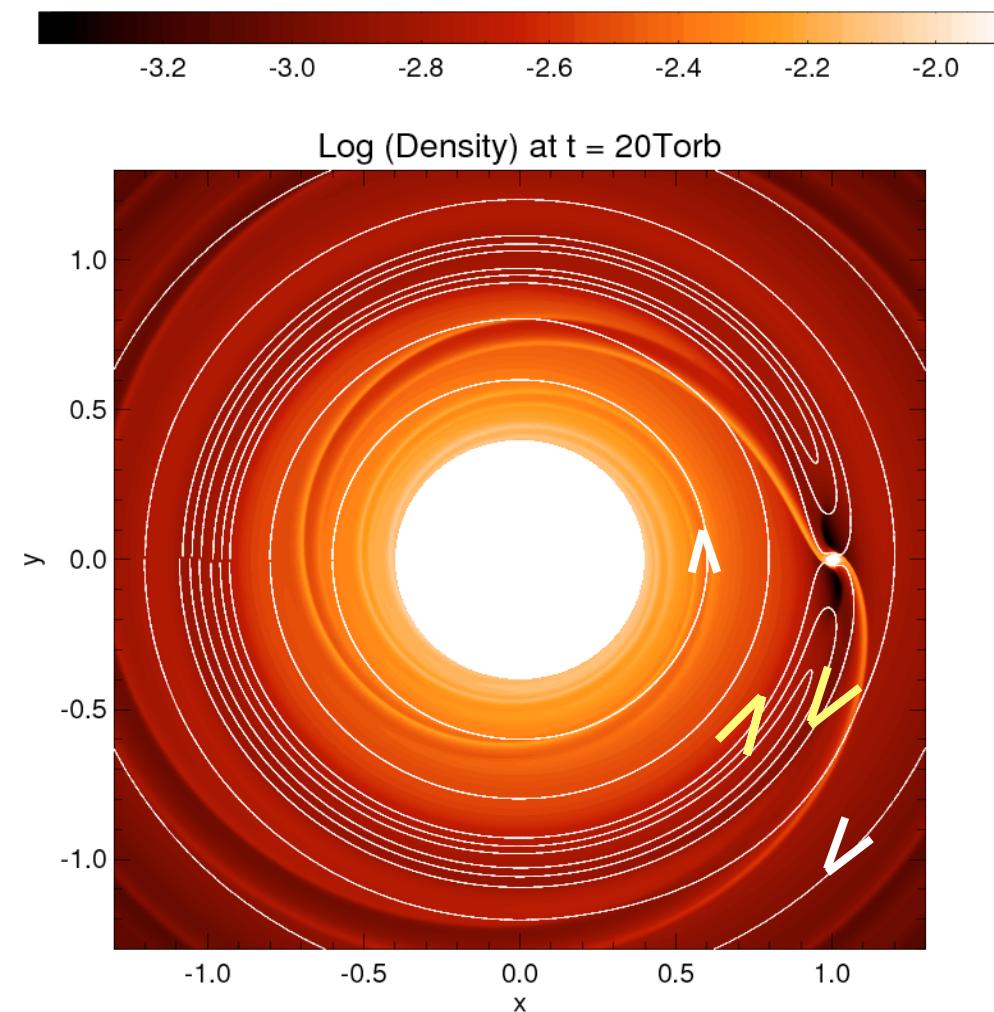
Gas giants: some key issues

- Is there a prefer location for gas giant formation?



Theoretical Paradigm: planetary migration

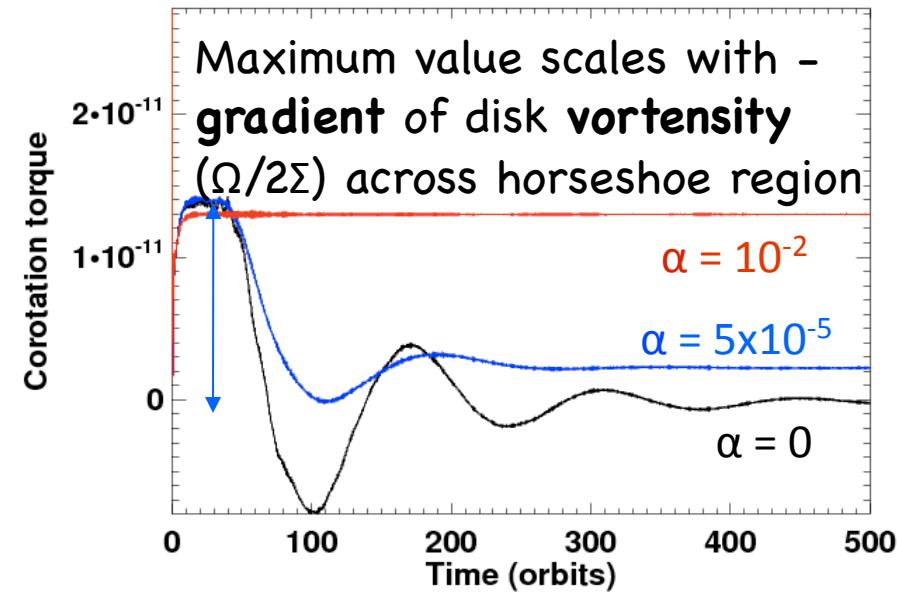
Type I migration of super-Earth in isothermal disks



e.g. Goldreich & Tremaine (1980),
Ward (1992), Masset (2001)

The planet exchanges angular momentum with:

- circulating fluid elements:
→ differential Lindblad torque
- librating fluid elements:
→ corotation torque



Long-term evolution of the corotation torque is related to the disk viscosity
Paardekooper, Baruteau,

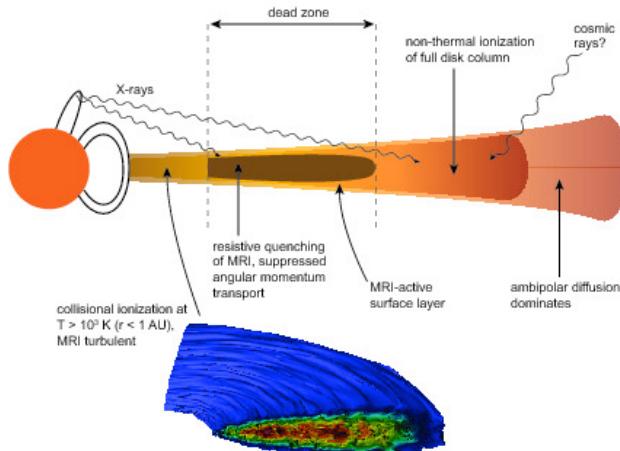
Planet-disk tidal interaction

Total tidal torque:

$$\Gamma = \Gamma_L + \Gamma_e = f(p, q, p_\nu, q_\nu, p_K, q_K) \Gamma_0$$

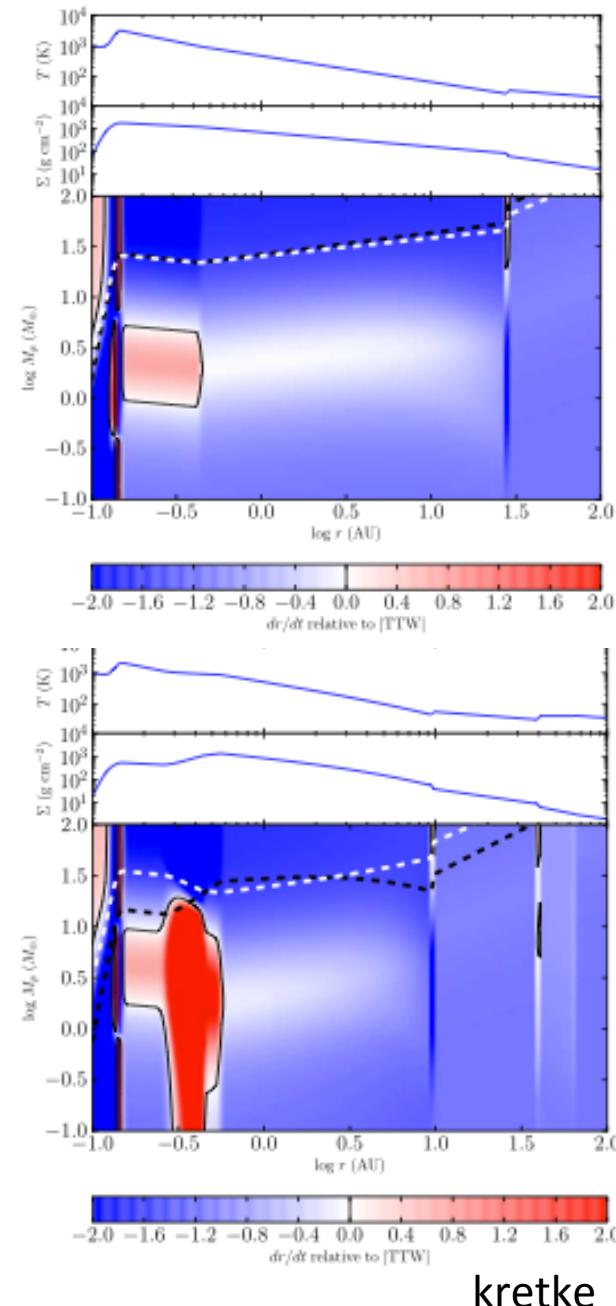
$$\Gamma_0 = (q/h)^2 \Sigma_p r_p^4 \Omega_p^2,$$

p and q depend on disk structure &
 p_ν, q_ν, p_K , and q_K also depend on m_p



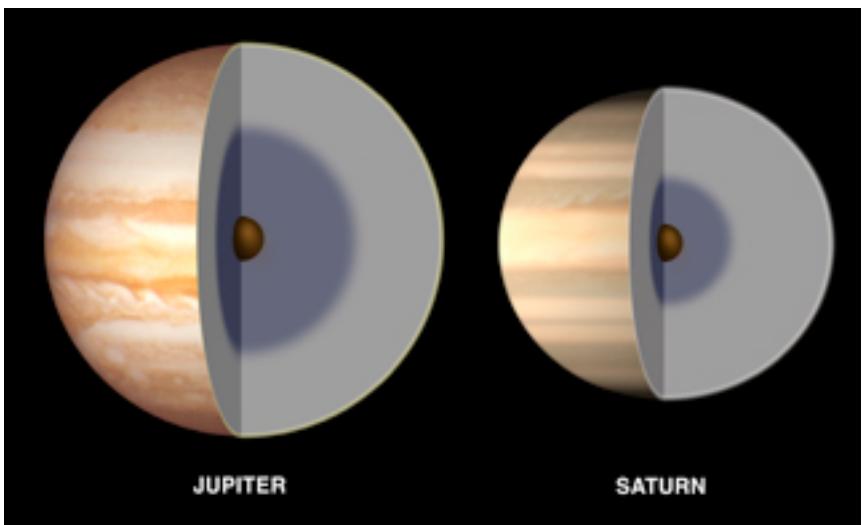
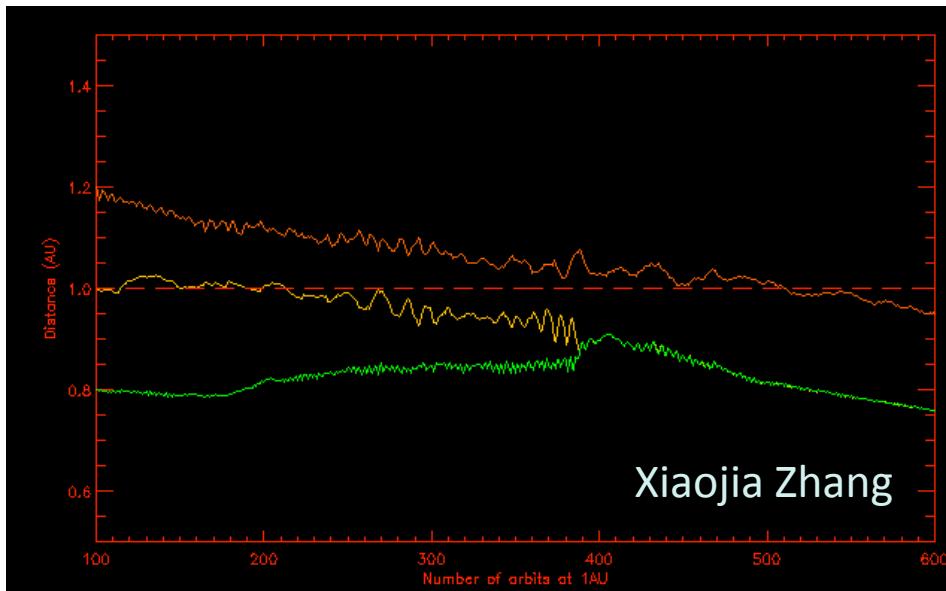
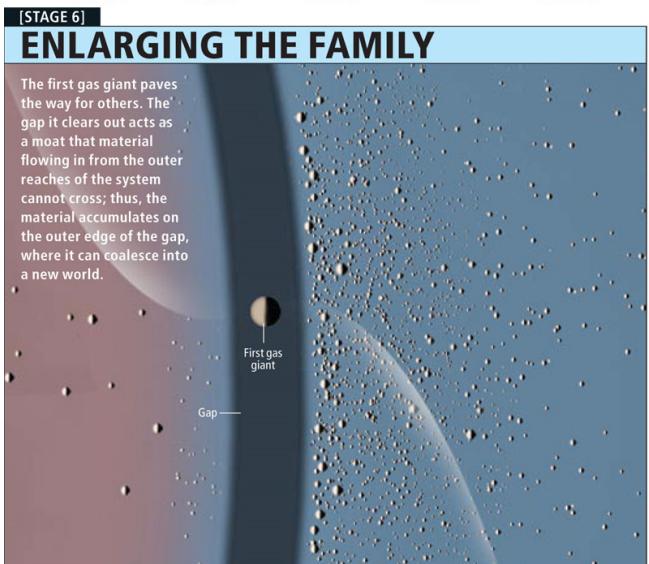
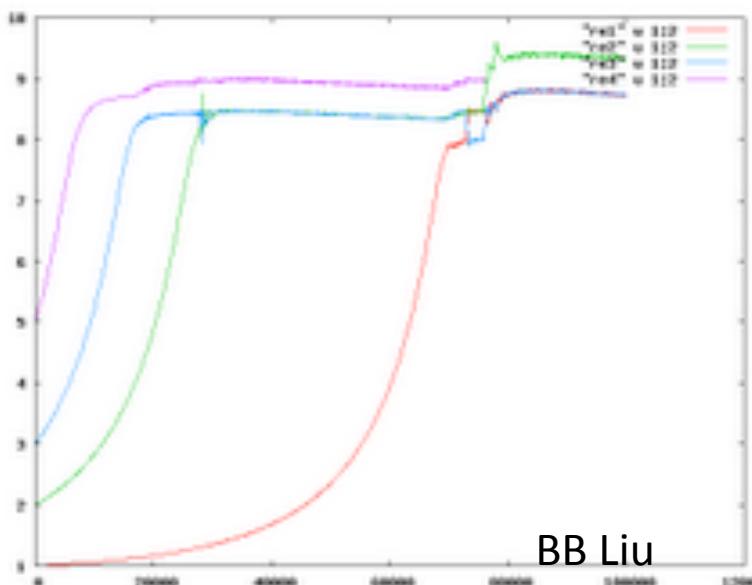
$$\frac{dr}{dt} = f(p, q, p_\nu, p_K) \frac{M_p}{M_*} \frac{\Sigma r^2}{M_*} \left(\frac{r \Omega_K}{c_s} \right)^2 r \Omega_K$$

$$(1/e)de/dt = (a/H)^4 (M_p \Sigma a^2 / M_*^2) \Omega$$



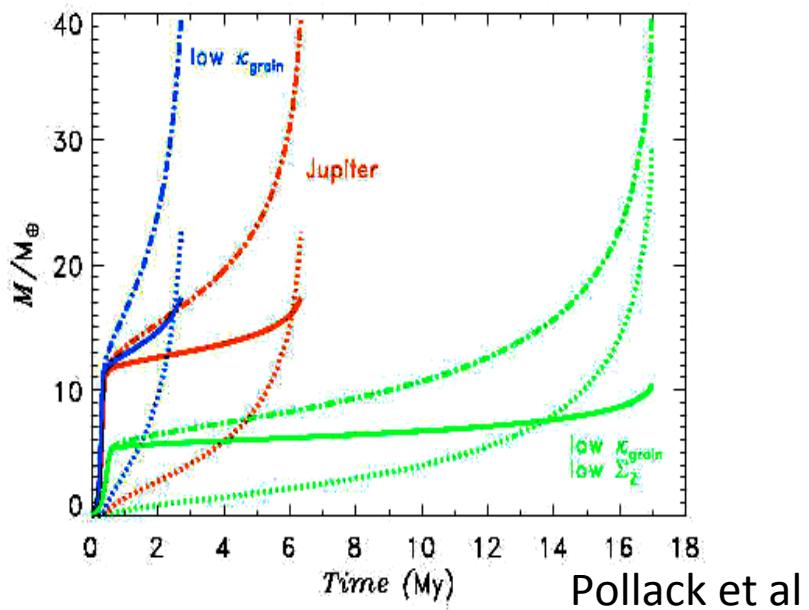
Gas giants: some key issues

- Can cores form prolifically?

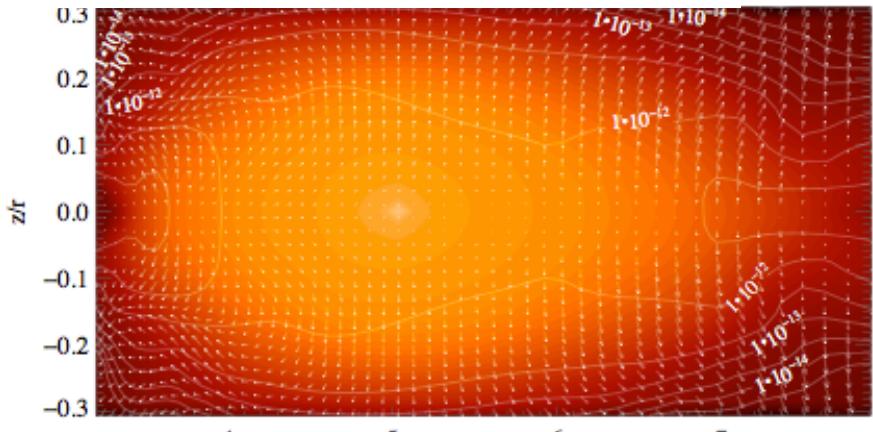


Gas giants: some key issues

- Is there a threshold mass for gas accretion?



Pollack et al



Radiation transfer & gas accretion

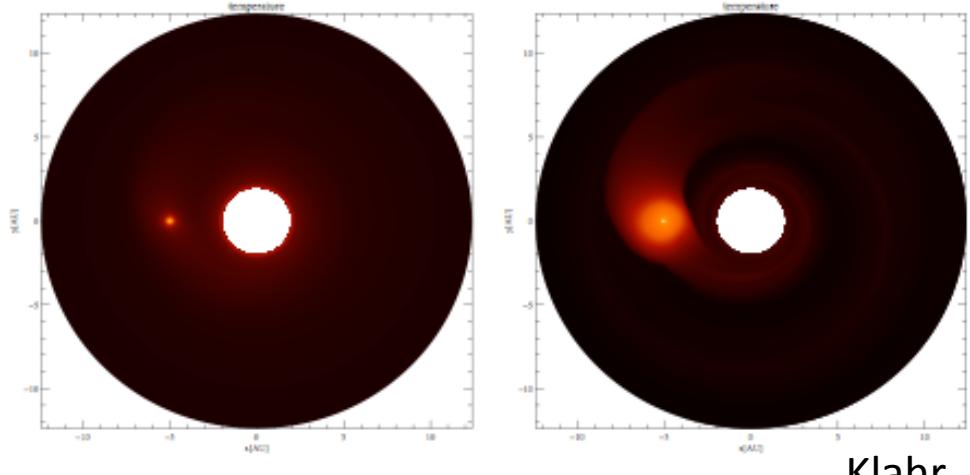
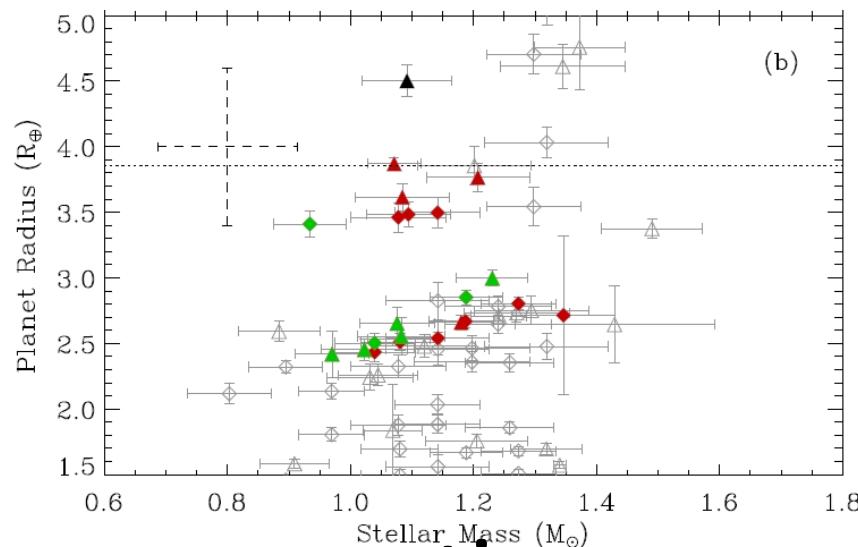
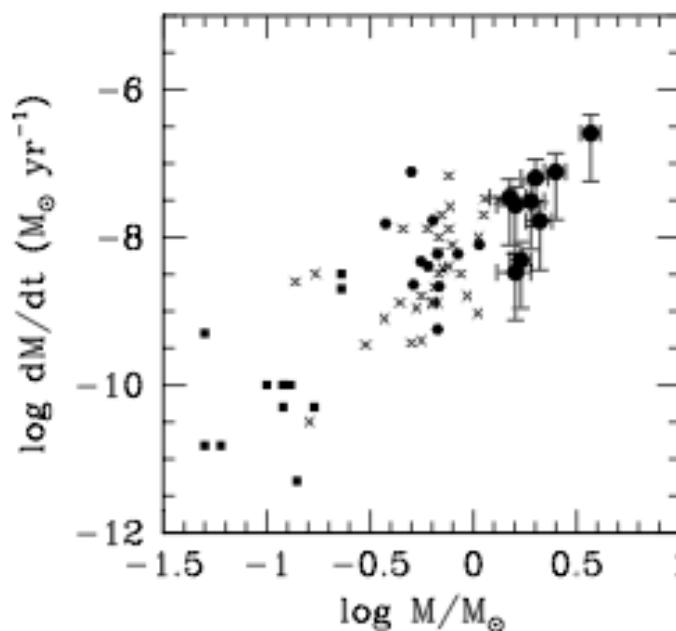
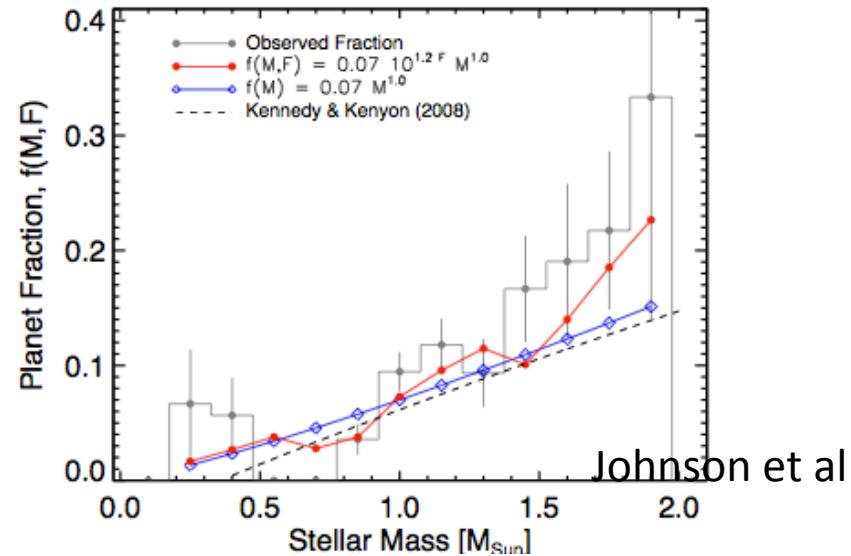
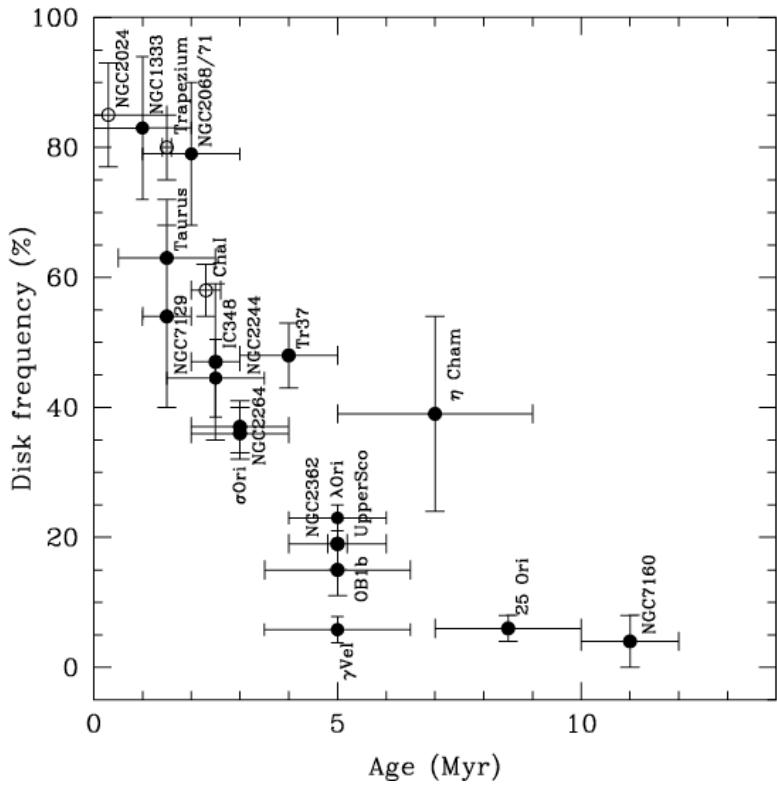


Fig. 4.— Temperature distribution - left: $30M_{\oplus}$ and $\kappa = 0.01\kappa_0$; right: $30M_{\oplus}$ and $\kappa = 1\kappa_0$



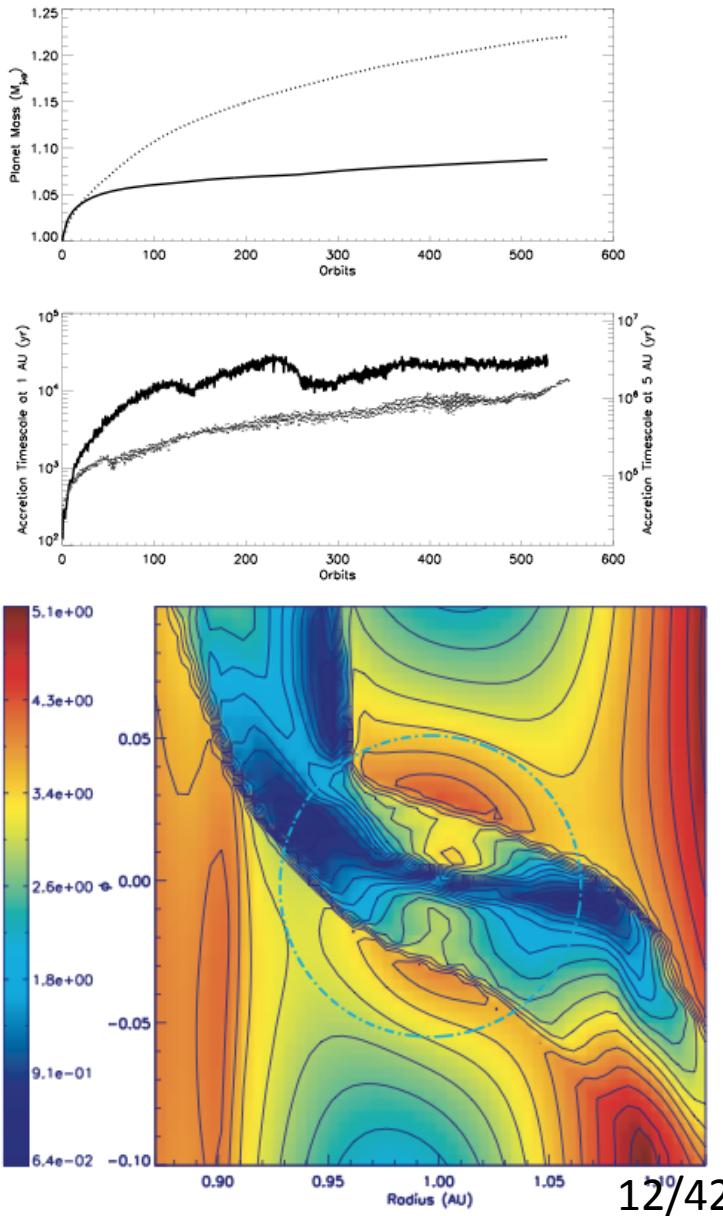
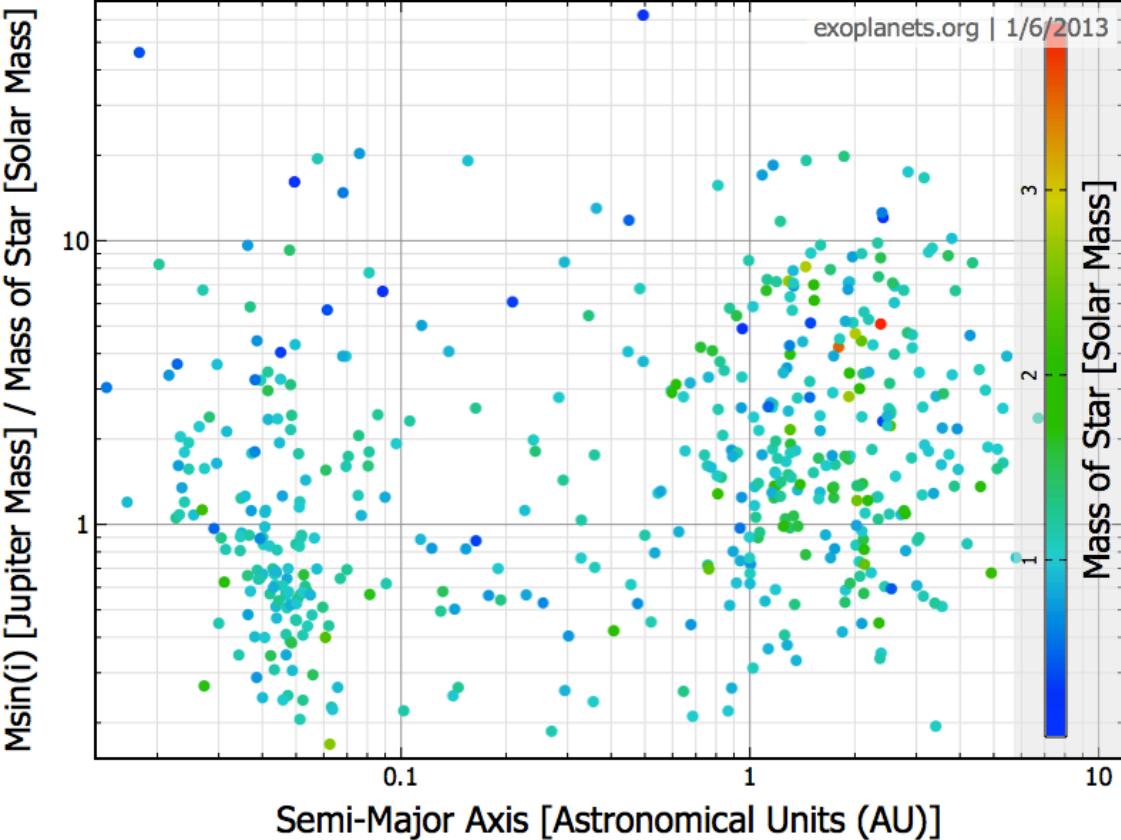
Gas giants: some key issues

- Is there enough time for gas giant to form?



Gas giants: some key issues

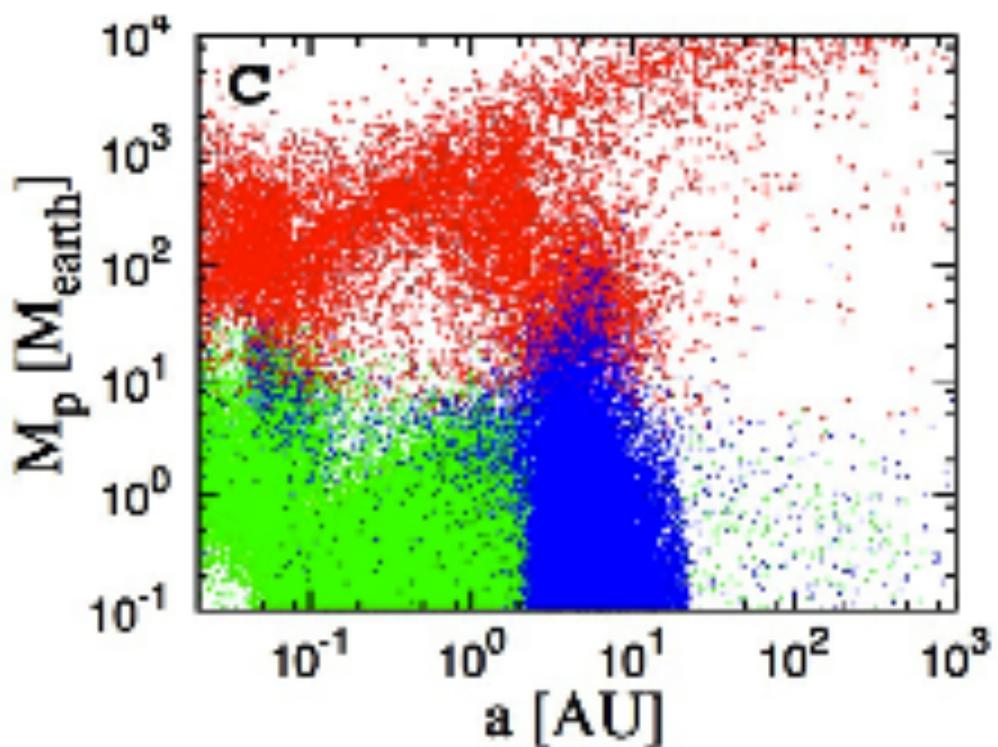
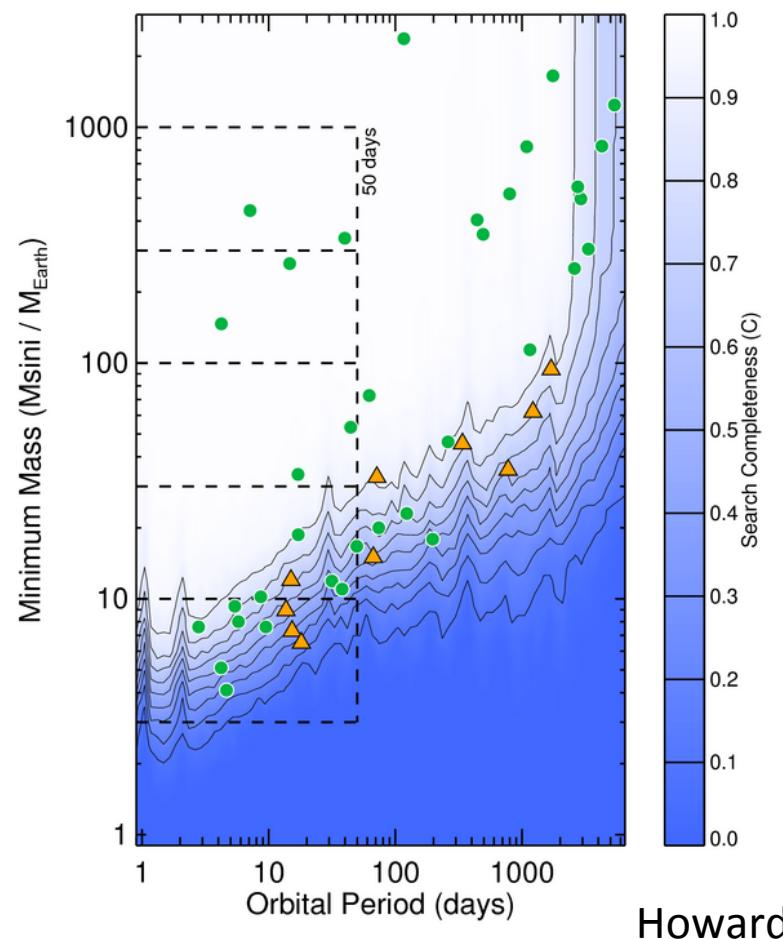
- Is there an upper mass limit for gas accretion?



Dobbs-dixon, Li

Gas giants: some key issues

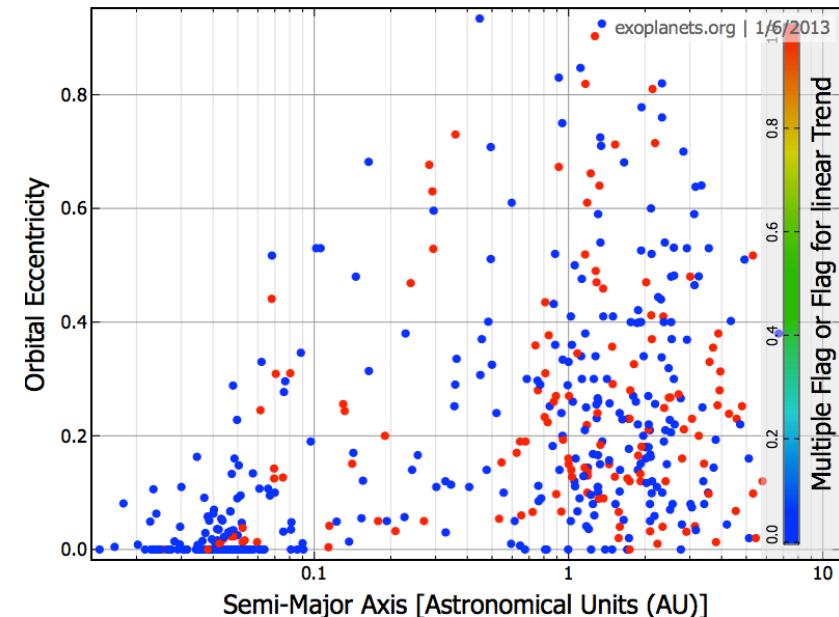
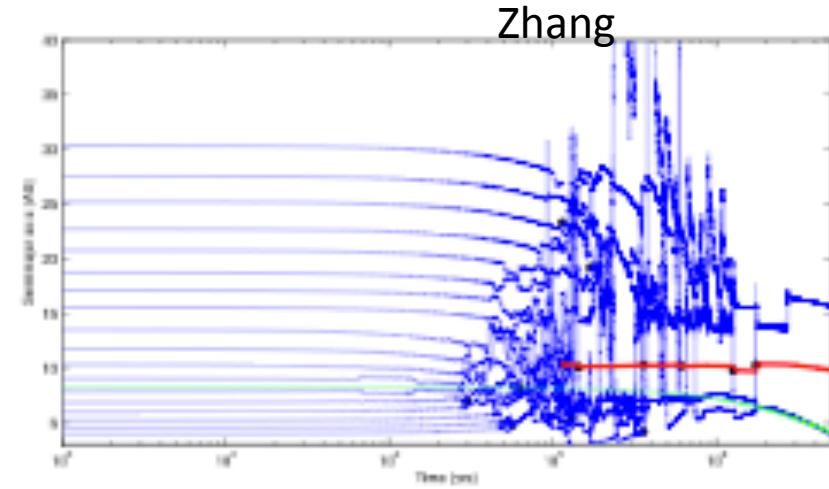
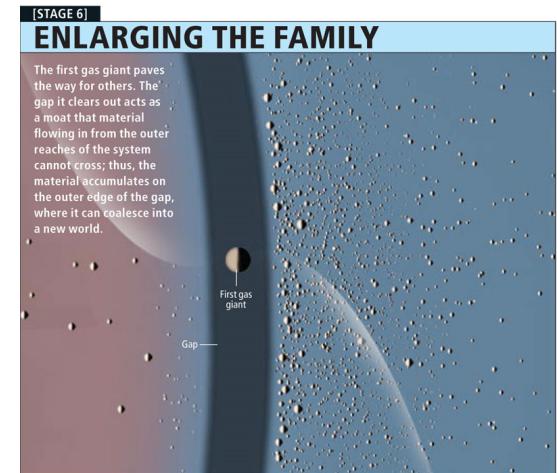
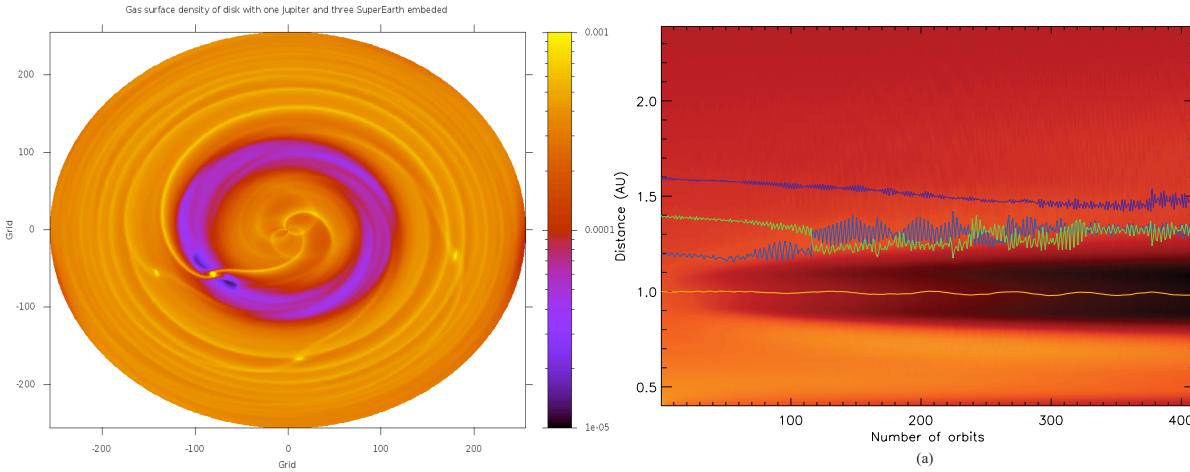
- Where is the planetary desert predicted by population
- Synthesis models?



Ida

Gas giants: some key issues

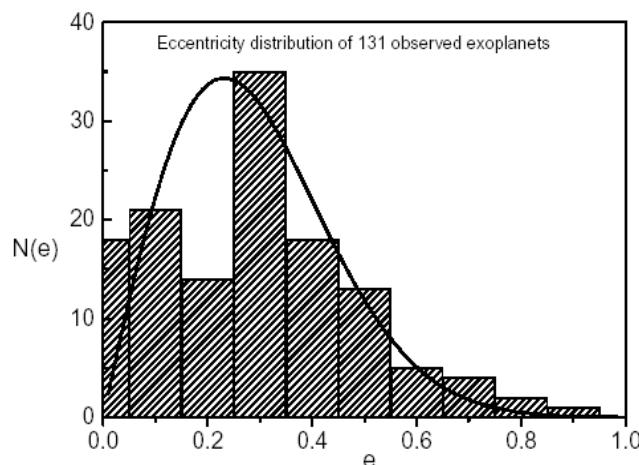
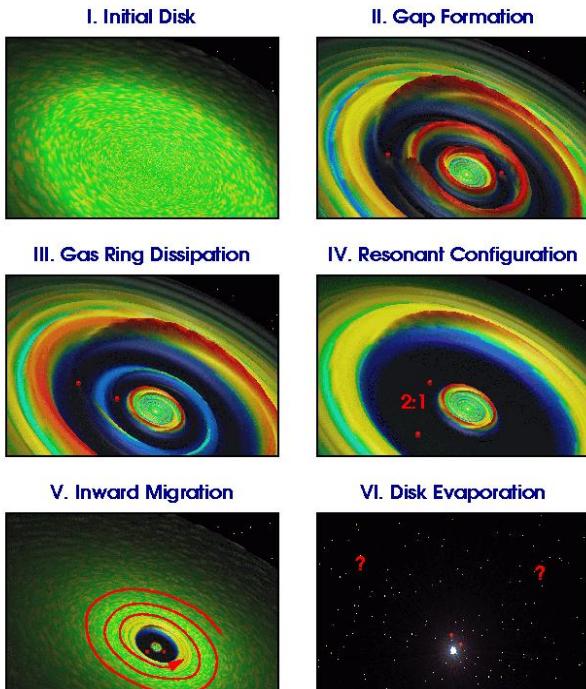
- How did multiple gas giant system form?



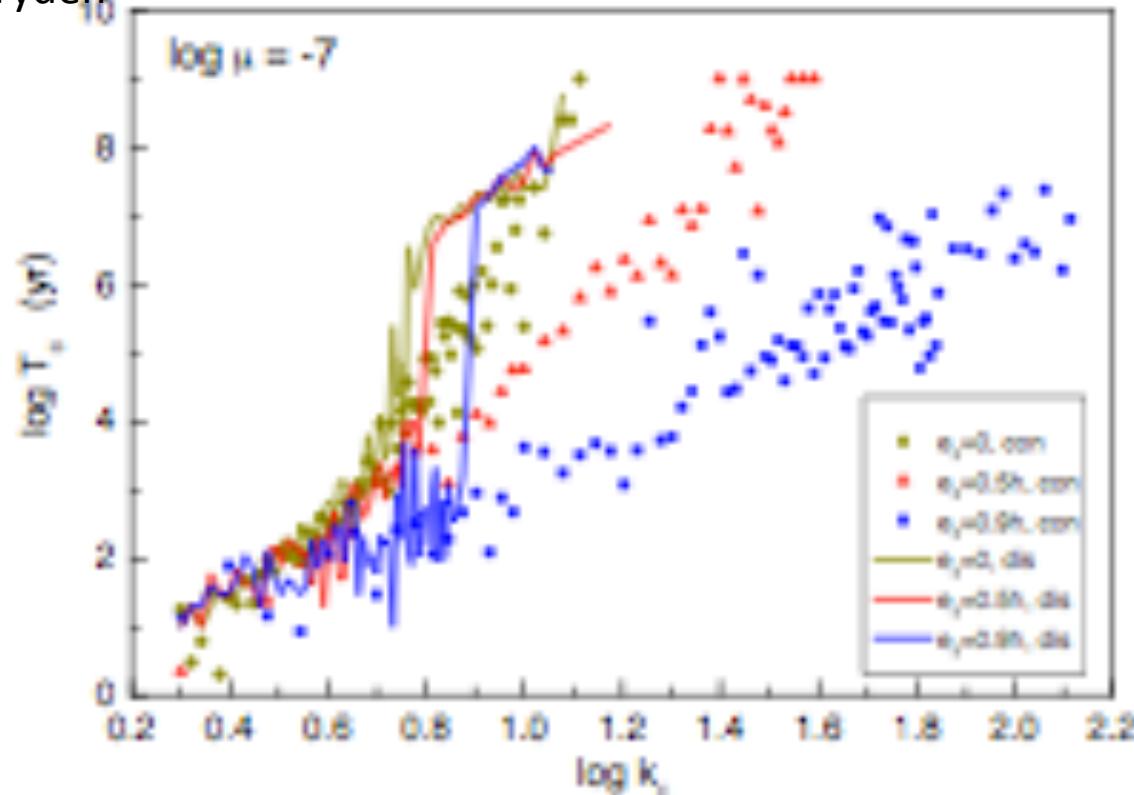
Astrometry, microlensing, direct imaging

Gas giants: some key issues

- How did gas giants acquire their eccentricity?



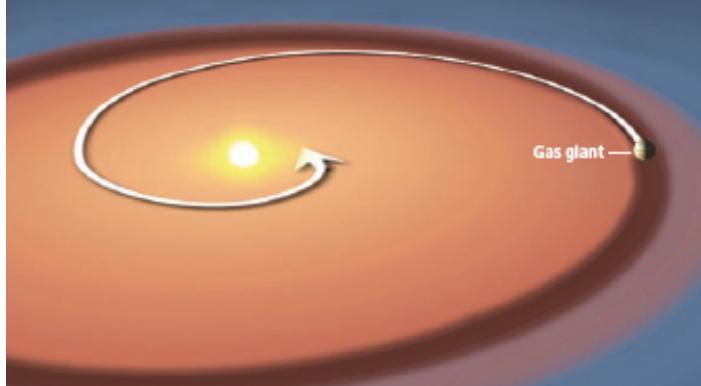
Bryden



Jilin Zhou

Gas giants: some key issues

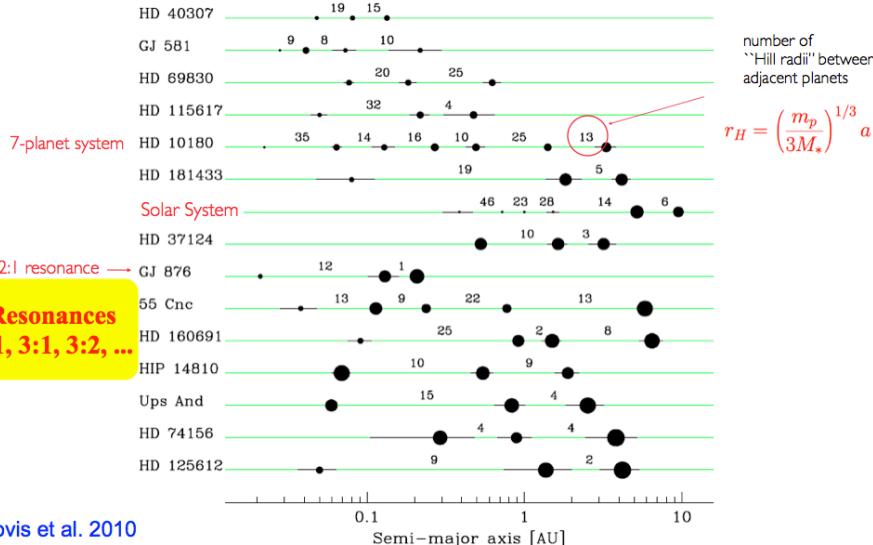
- How prevalent is gas giants' migration?
- How do lone gas giants migrate?



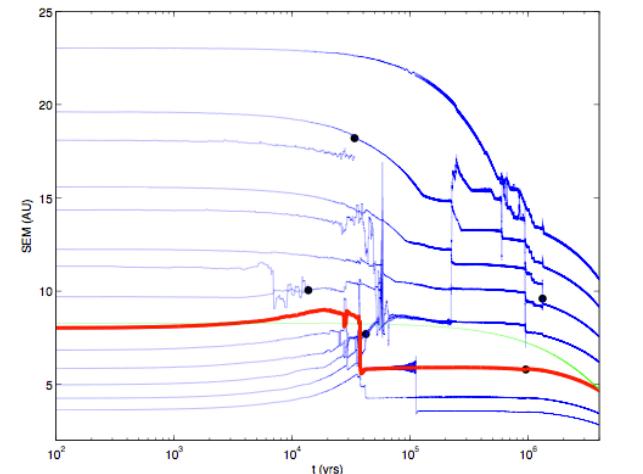
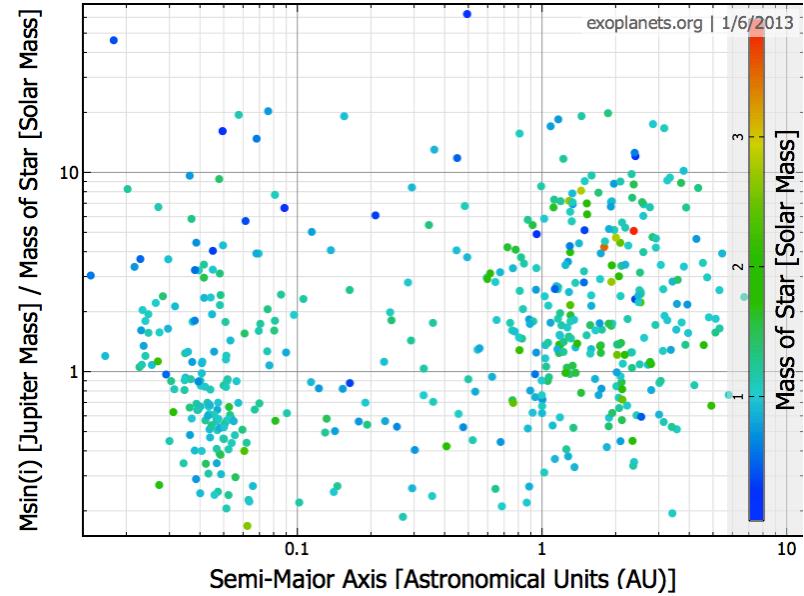
Systems with $n > 2$ planets

multi-planet systems: many are almost optimally ``packed''

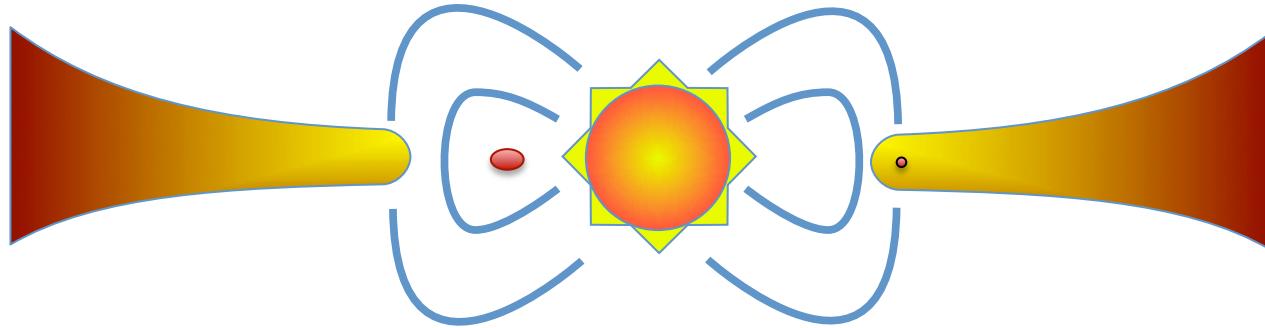
Also a constraint for
planet formation models!



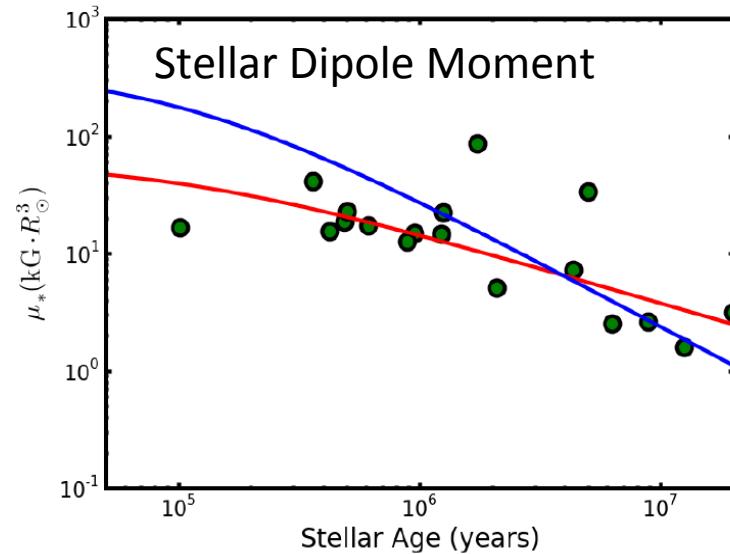
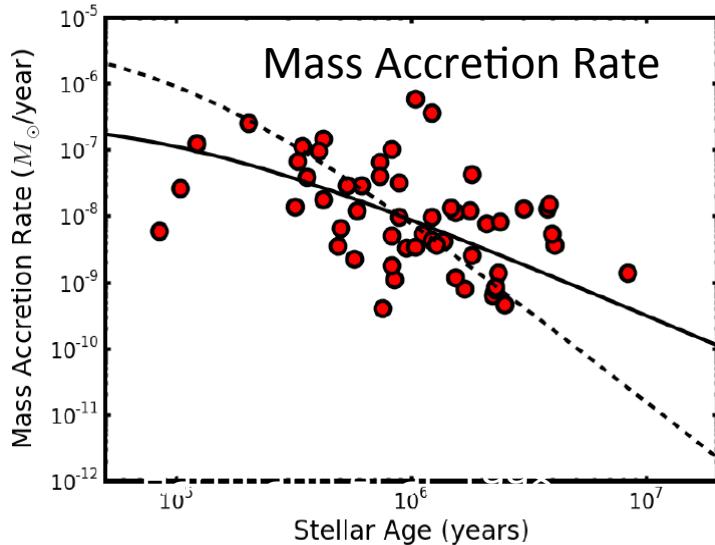
Lovis et al. 2010



Stalling of planets inside & at the magnetospheric truncation radius

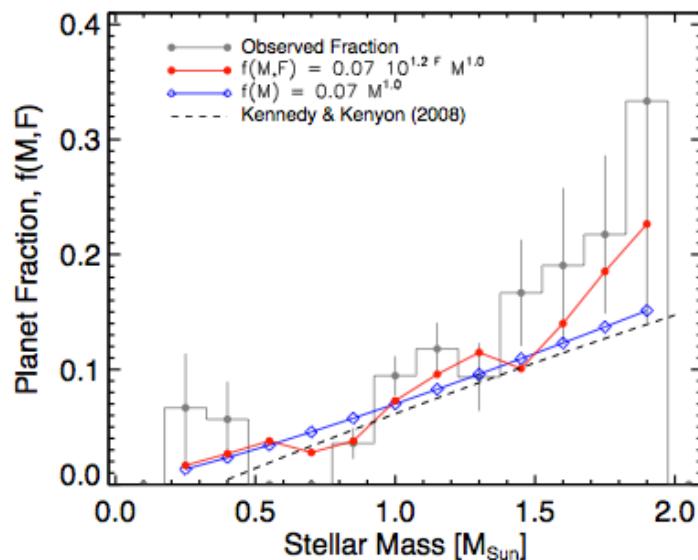


$$r_{\text{mag}} \propto \mu_*^{4/7} \dot{M}^{-2/7}$$

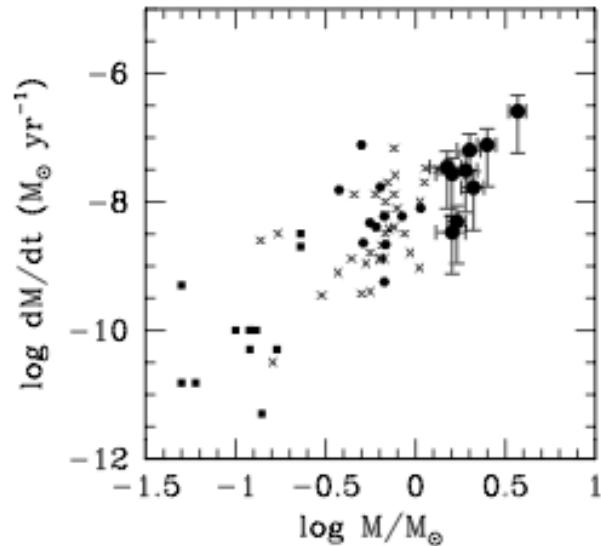


Herczeg

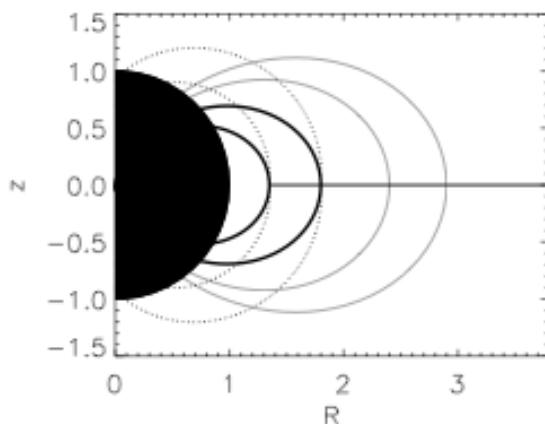
Paucity of hot Jupiters around hot stars



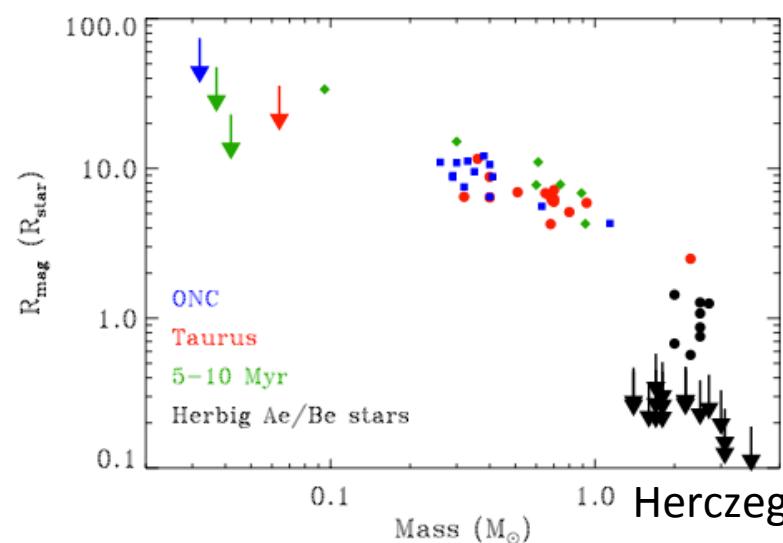
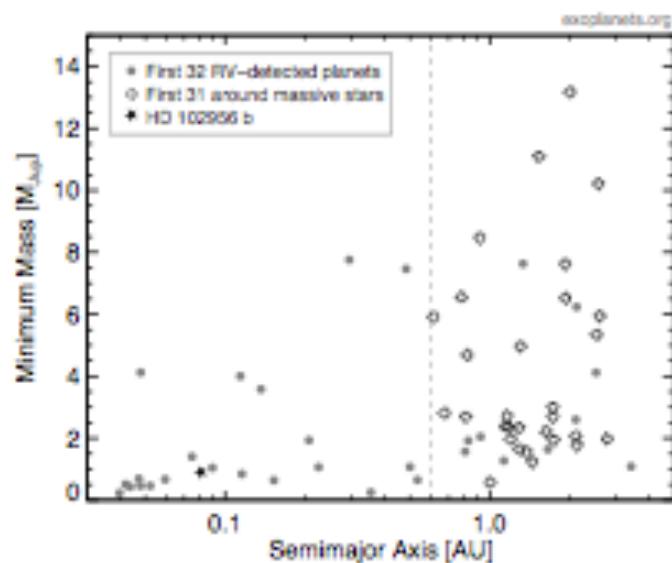
Johnson et al 2010a,b



Calvet et al 2005

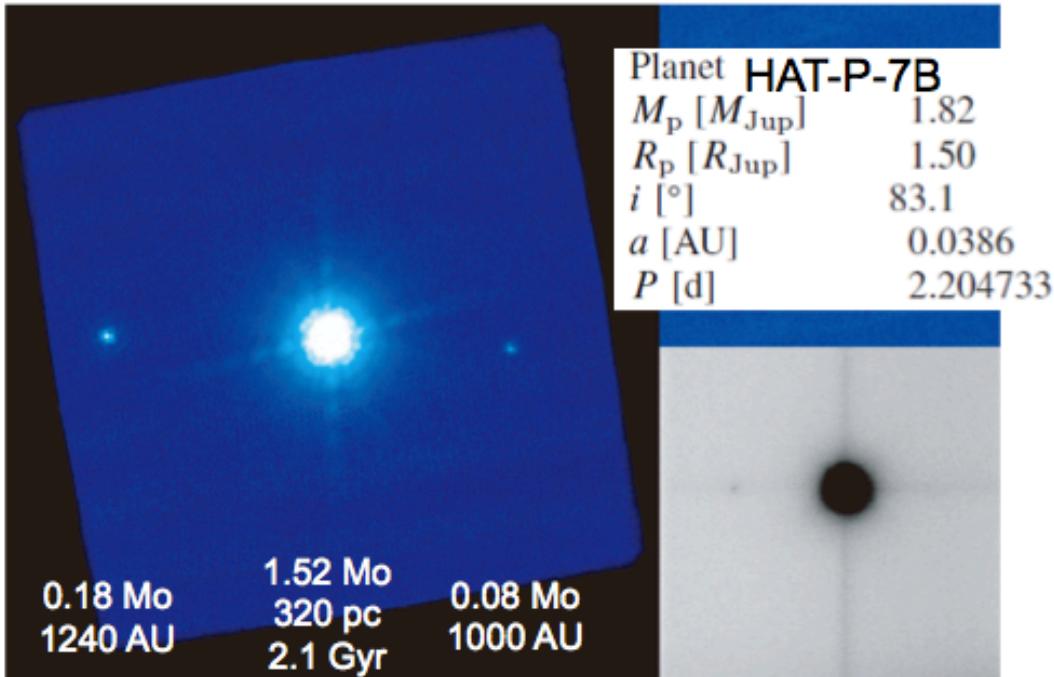


Muzerolle et al 2004



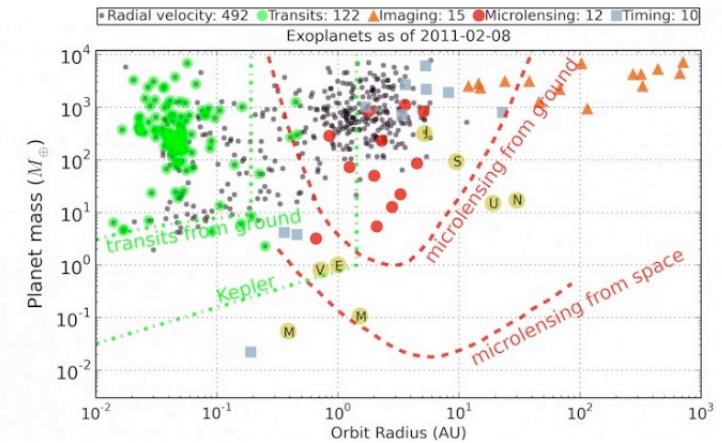
Gas giants: some key issues

- Where are the culprits for Kozai or secular chaos ?

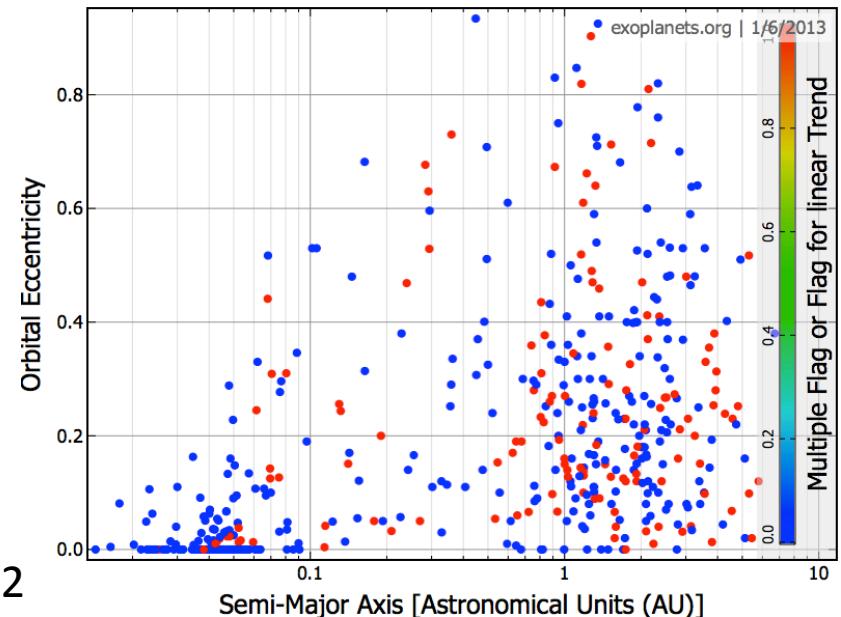


1.6 um image of HAT-P-7 (12"x12"). Upper right: A ADI/LOCI reduced Subaru image (""). Lower right: AstraLux z' band image of HAT-P-7 and the eastern companion candidate.

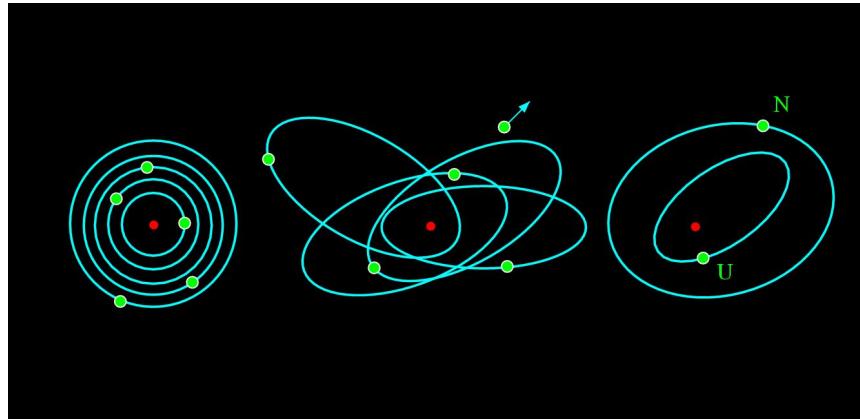
Wu, Murray



WFIRST, Direct Imaging

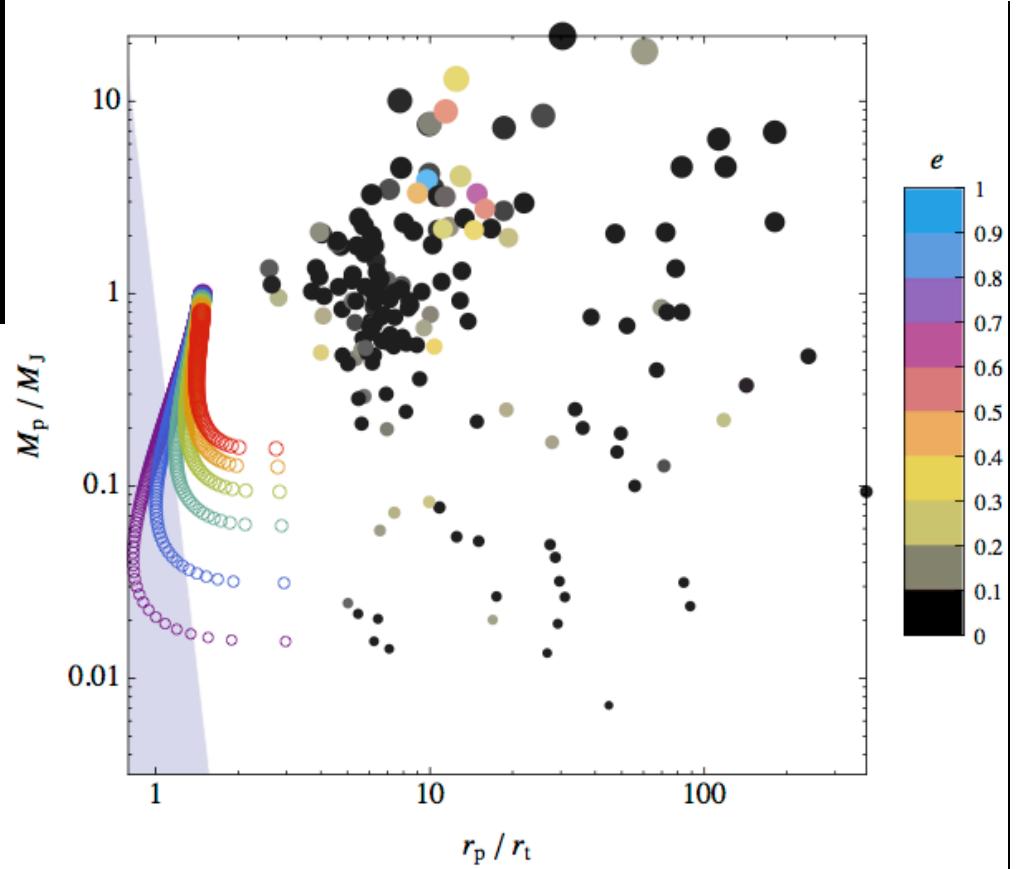
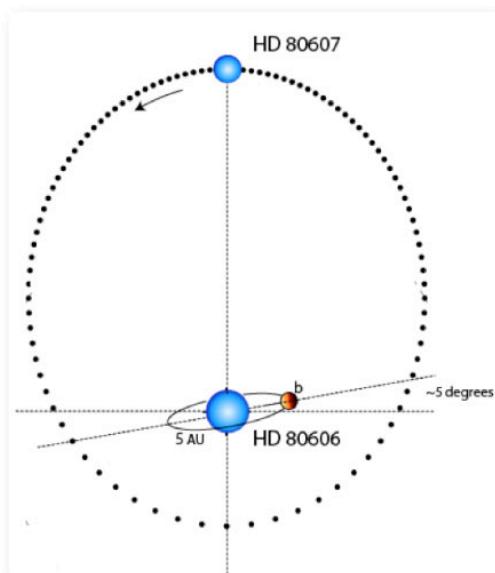


Tidal Disruption of a Jupiter-like Planet



A gas giant planet disrupted by a sun-like star as a result of planet-planet scattering or the Kozai effect.

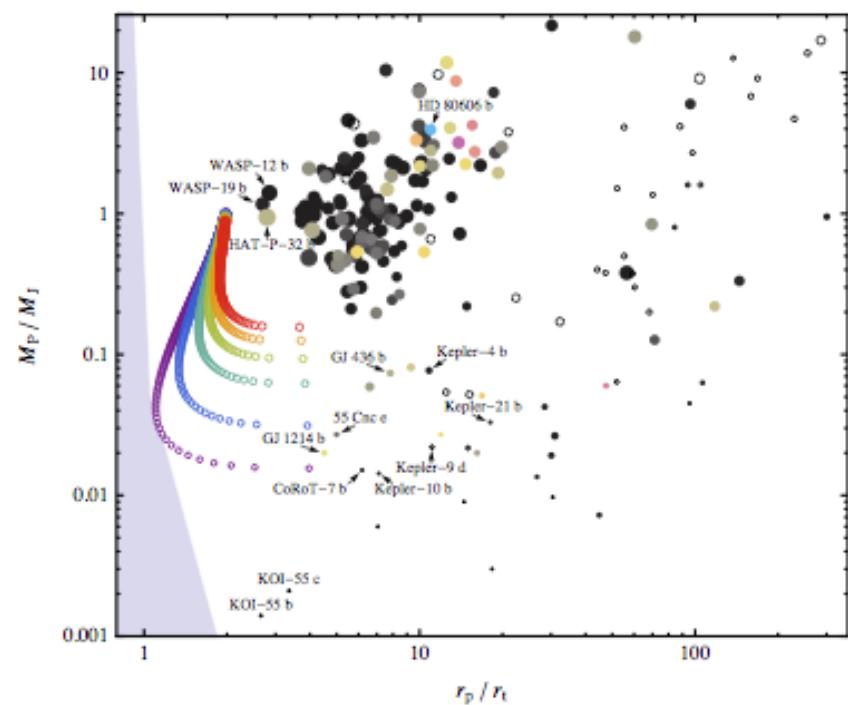
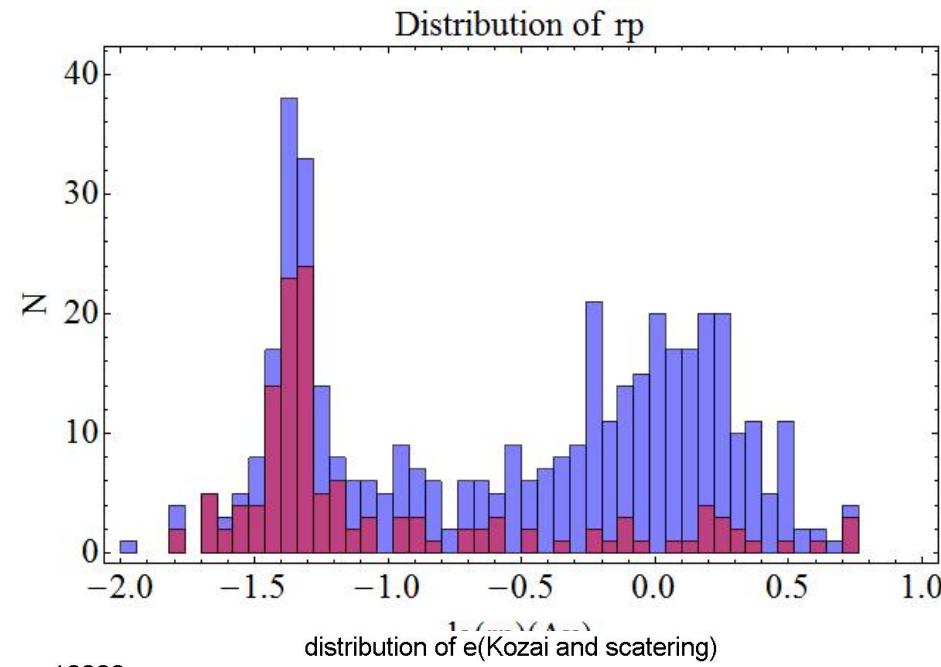
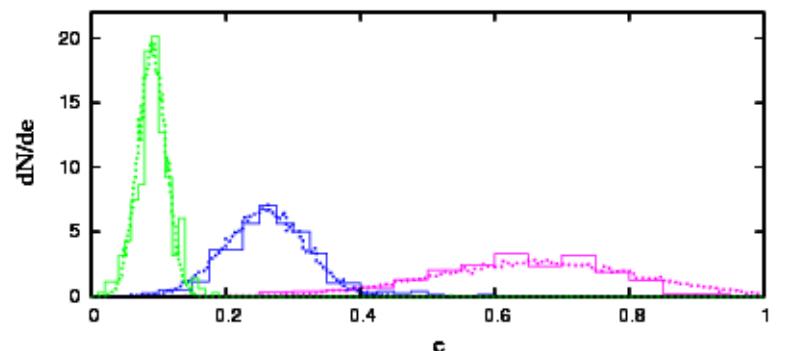
Nagasawa



By Shangfei Liu, Graduate Student @ KIAA, PKU

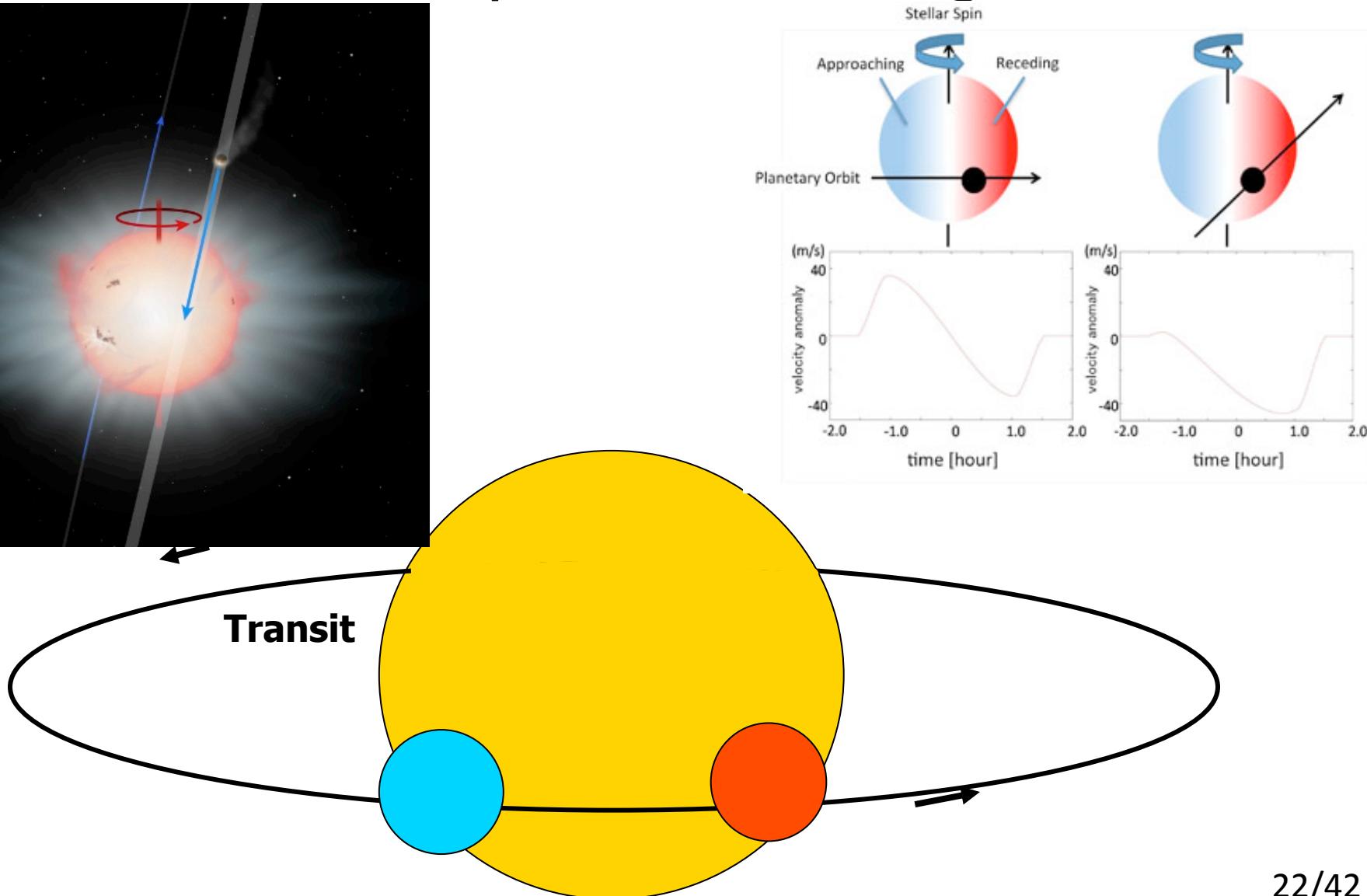
Gas giants: some key issues

- Is there evidence for prevalent spread scattering ?



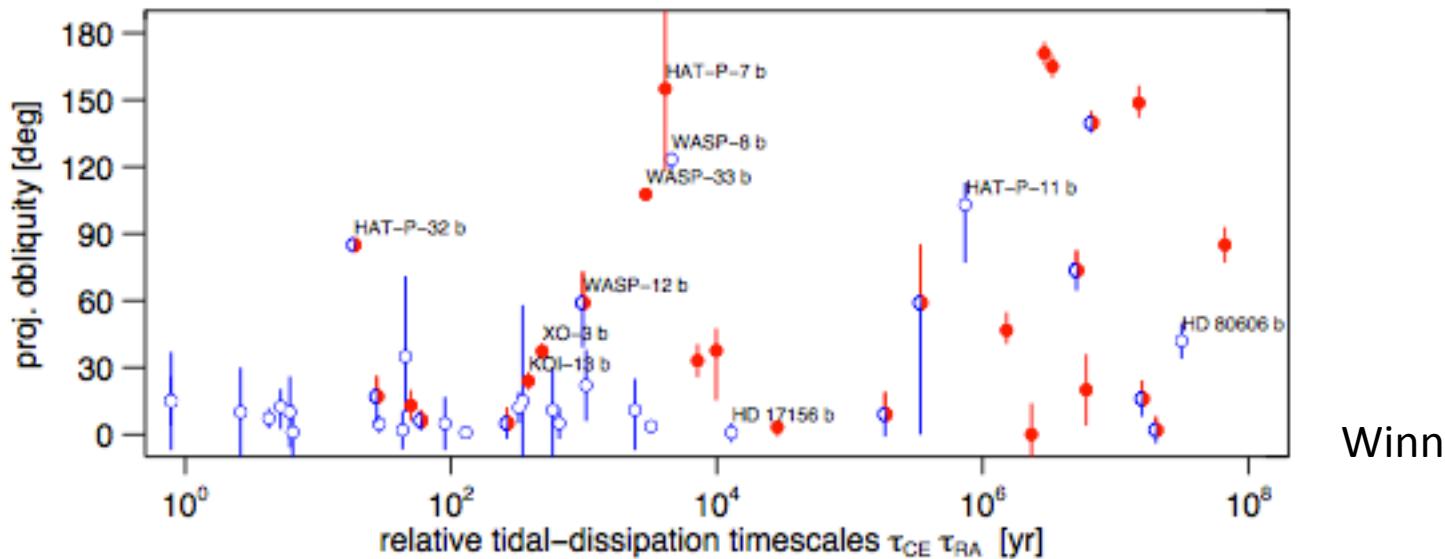
Gas giants: some key issues

What about spin-orbit misalignment?



Gas giants: some key issues

- Is there evidence for M_* -dependent tidal dissipation?



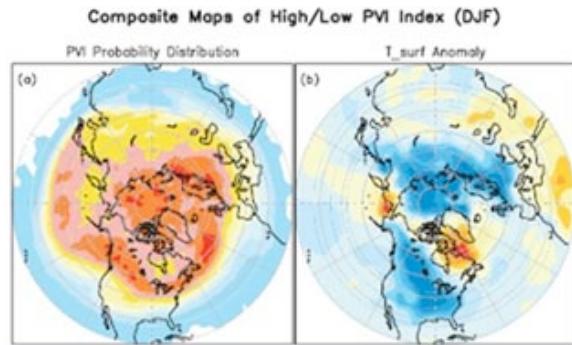
Winn

$$(\dot{\Theta})_{10} = -\frac{1}{t_{s10}} \sin\Theta \cos^2\Theta \left(\cos\Theta + \frac{S}{L} \right),$$

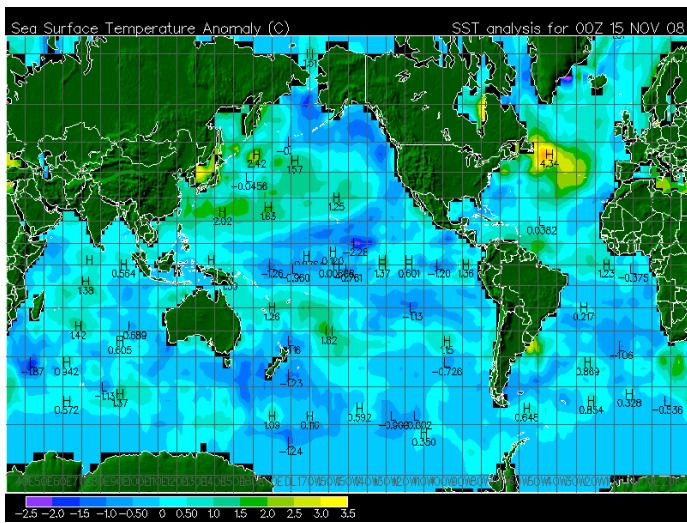
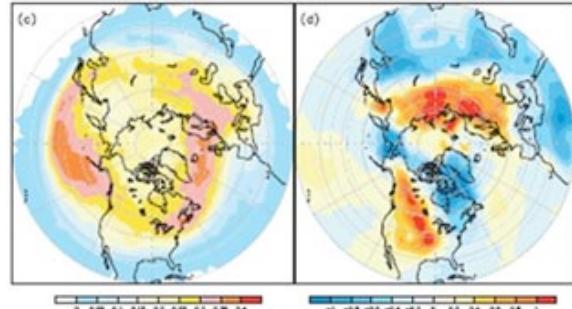
$$\begin{aligned} t_{s10} &= 4.3 \left(\frac{\kappa}{0.1} \right) \left(\frac{Q_{10}/k_{10}}{10^7} \right) \left(\frac{M_*}{10^3 M_p} \right)^2 \left(\frac{\bar{\rho}_*}{\bar{\rho}_{\odot}} \right) \\ &\times \left(\frac{10 \text{ d}}{P_s} \right) \left(\frac{P}{1 \text{ d}} \right)^4 \text{Gyr} \end{aligned}$$

Alternative model: internal gravity wave

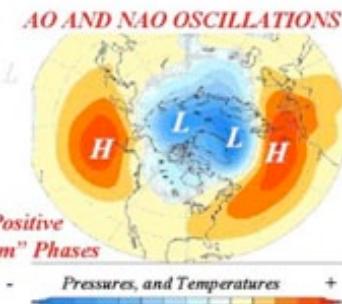
East QBO
Potential
Vorticity
Intrusion
Index



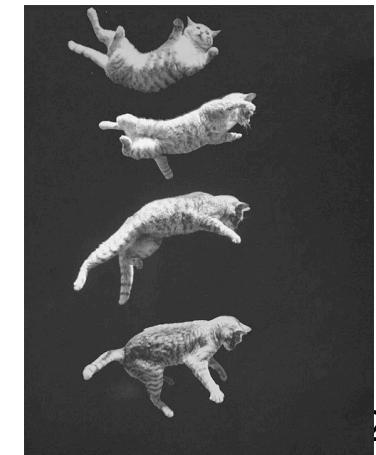
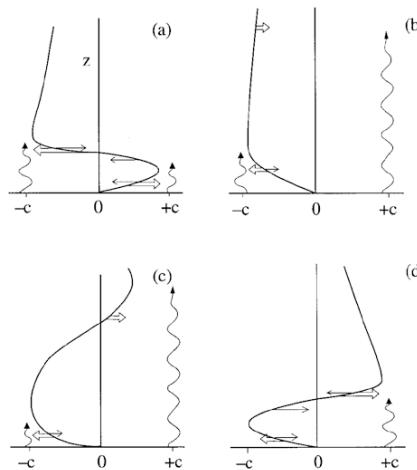
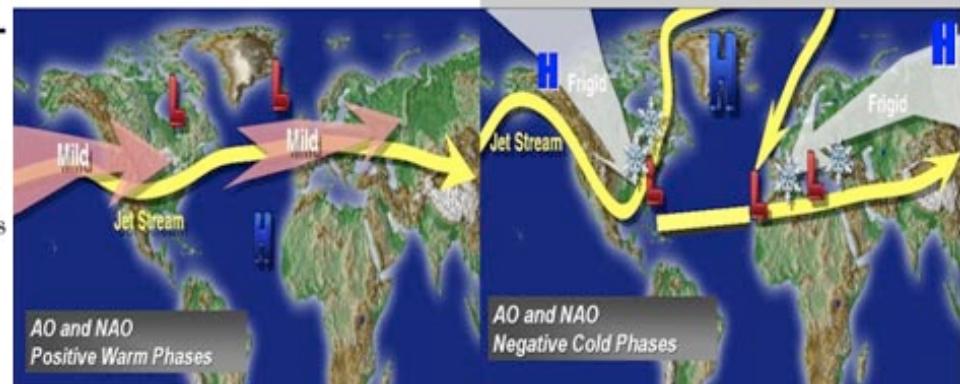
West QBO
Potential
Vorticity
Intrusion
Index



East
QBO
Temps



West
QBO
Temps

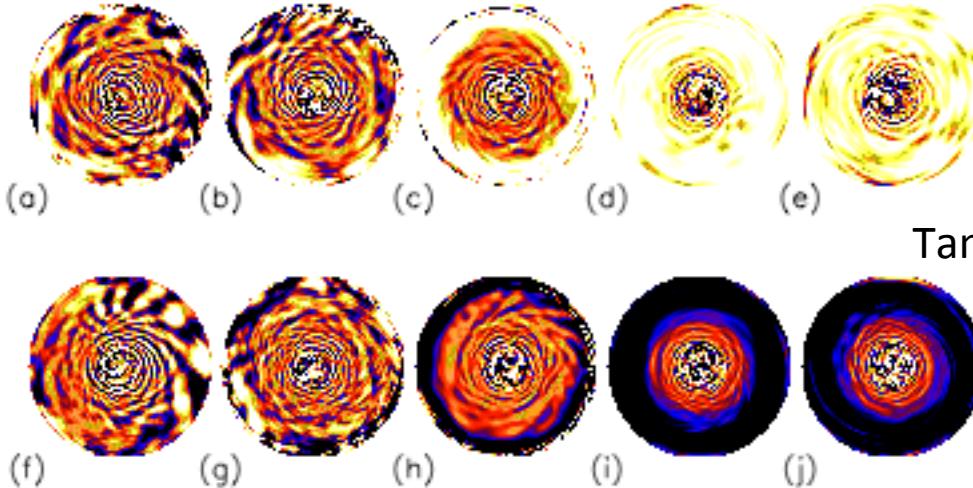


24/42

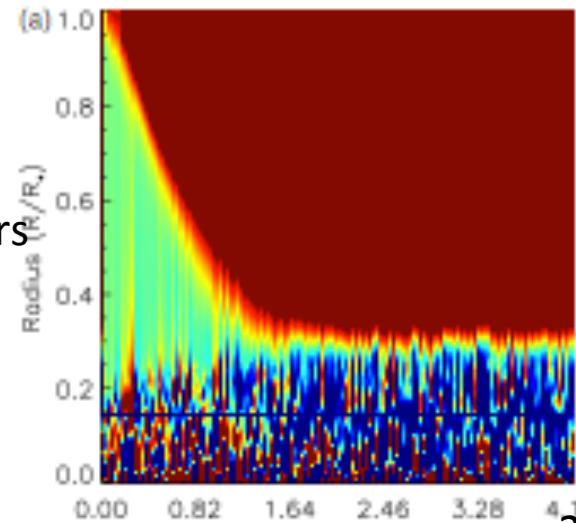
Tami Rogers

Gas giants: some key issues

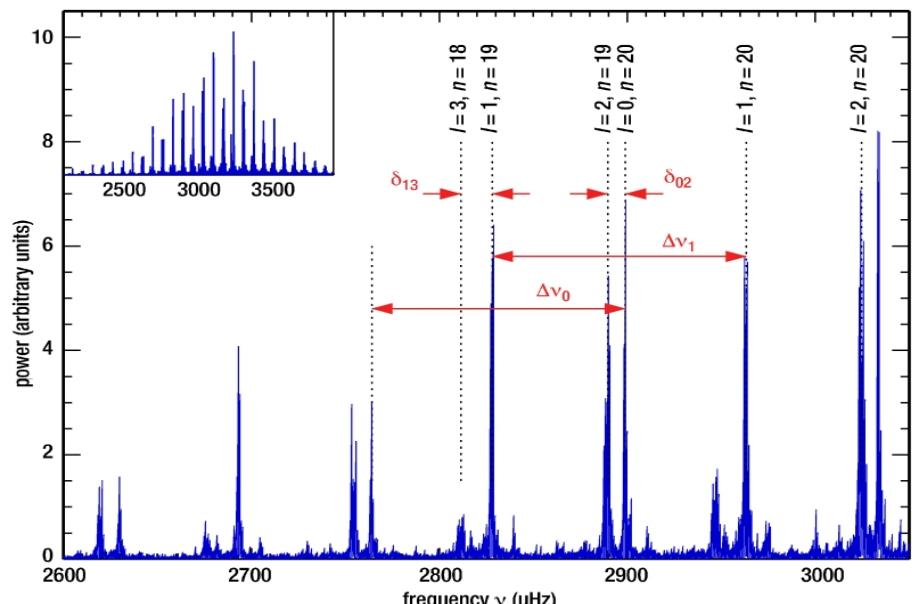
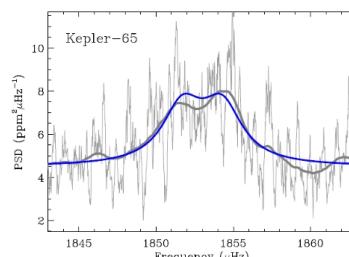
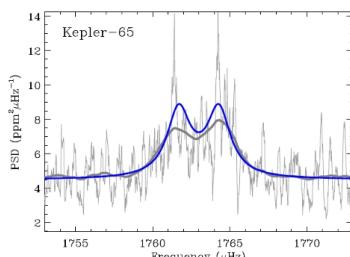
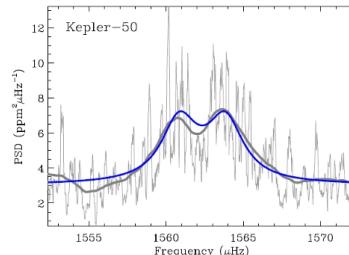
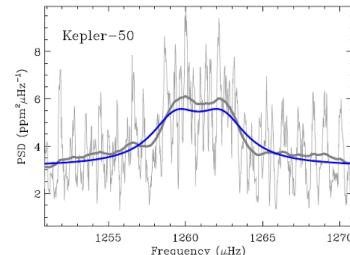
- Is there evidence for internal differential rotation ?



Tami Rogers

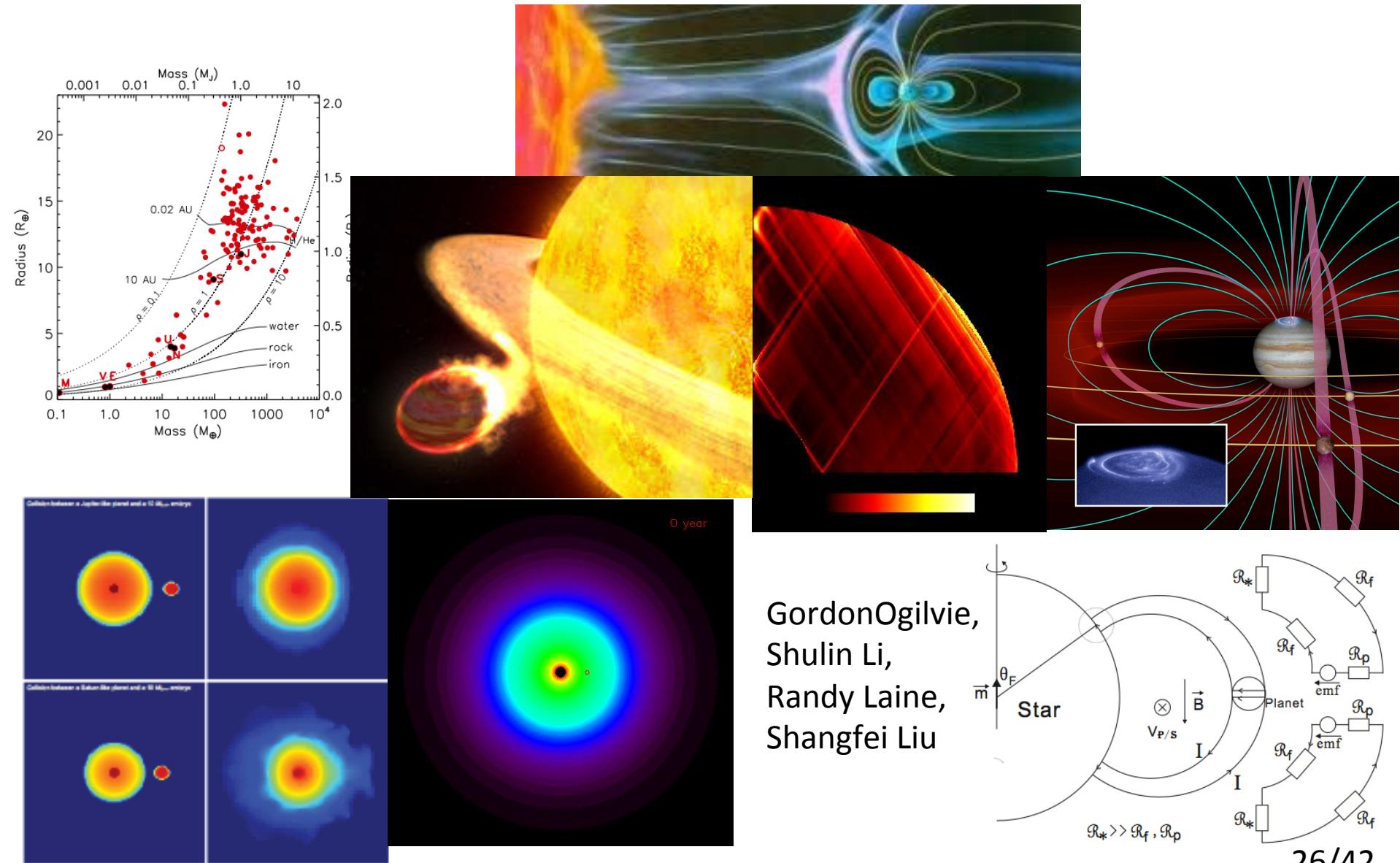


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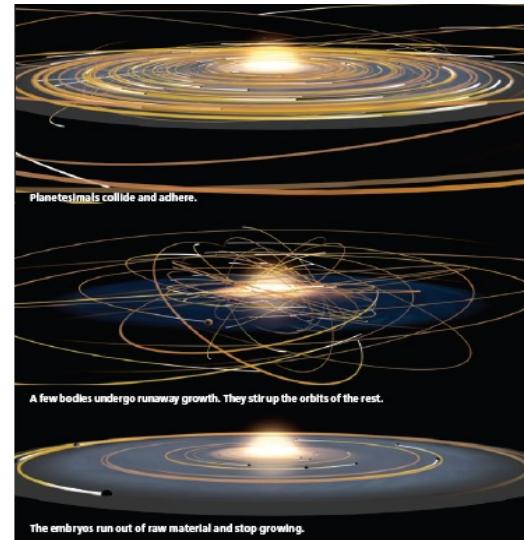
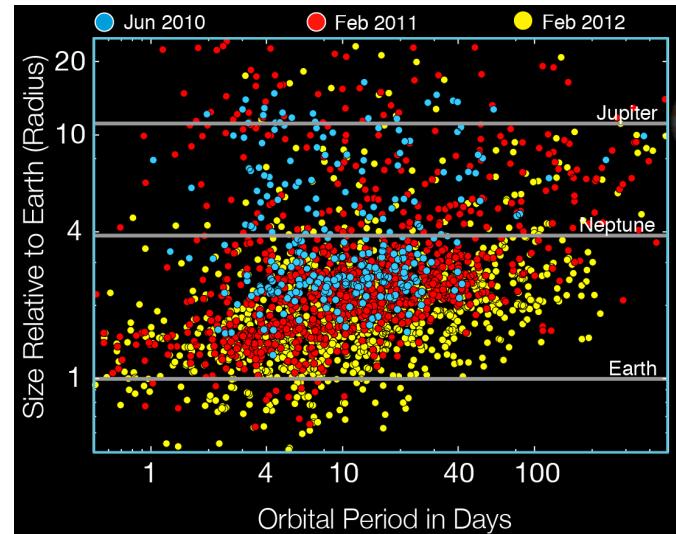
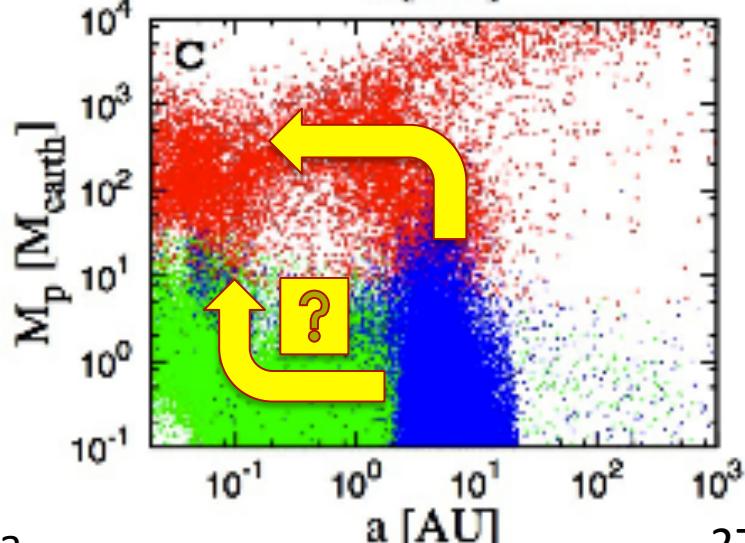
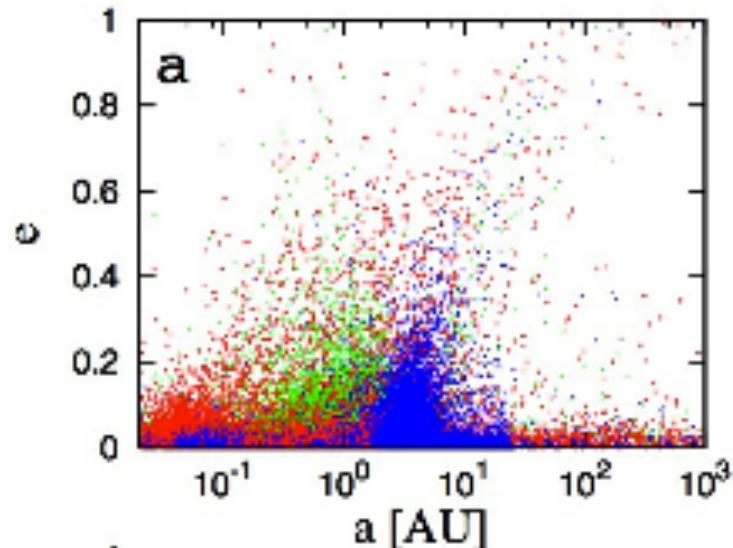
Gas giants: some key issues

- Origin of diverse planetary density ?



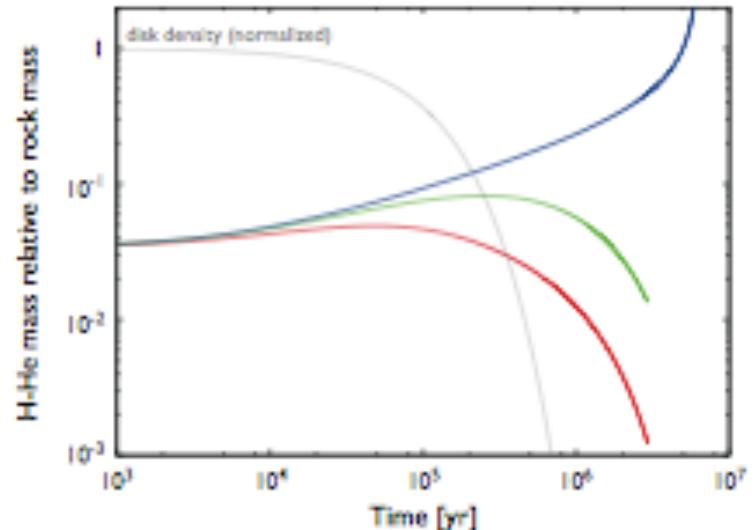
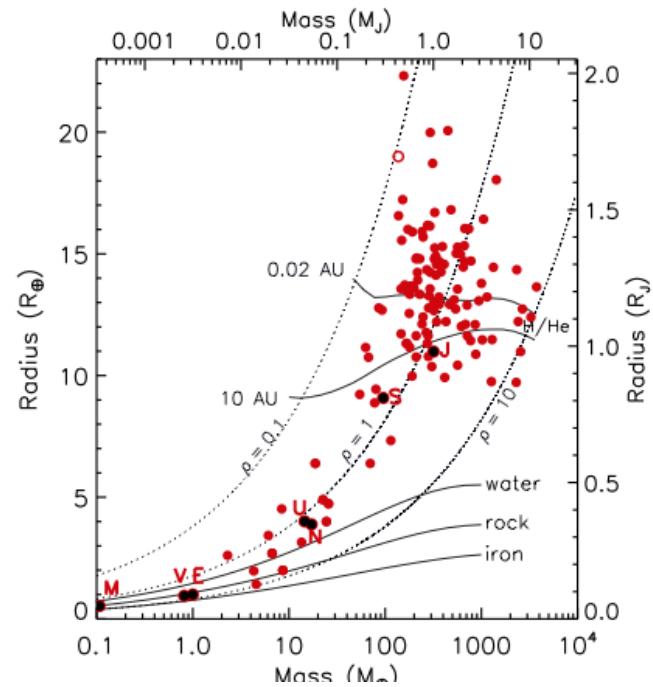
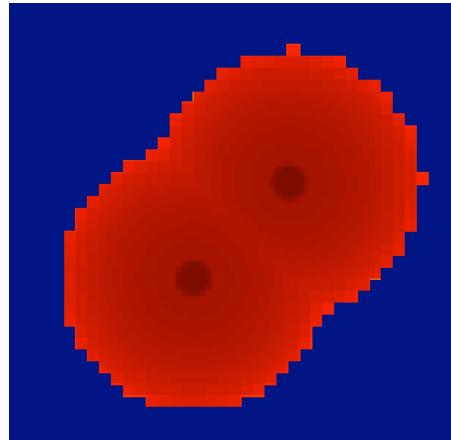
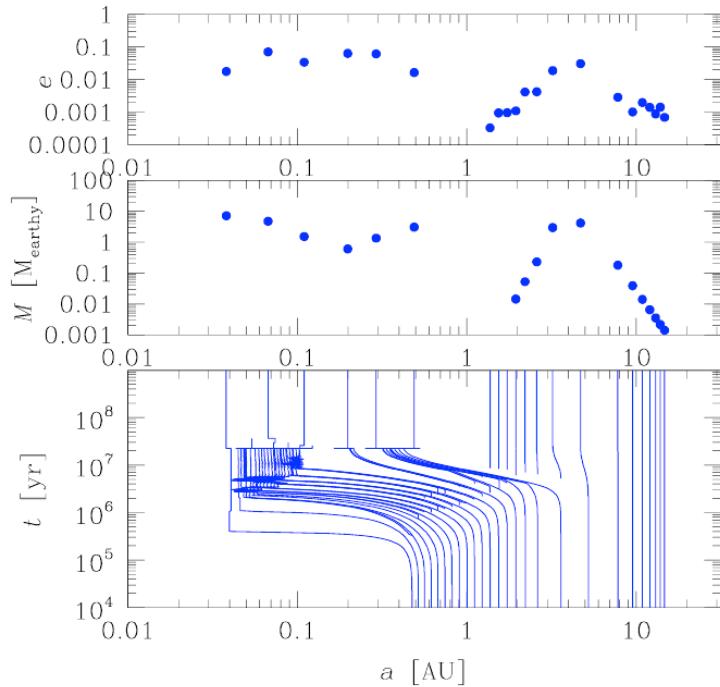
Super Earths: some key issues

- Did super Earths assemble in situ or form at large a and migrate?



Super Earths: some key issues

- How to identify *in situ* assembly?



For a $10M_e$ planet at 0.04AU

$$R_{\text{roche}} \sim 0.02a \sim 8R_e$$

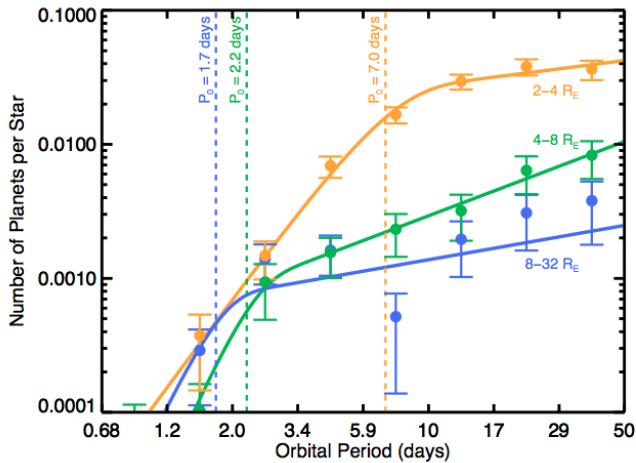
$$R_p \sim 2-3 R_e \sim 0.3 R_{\text{roche}}$$

$$R_m \sim R_{\text{roche}} \text{ if } B \sim 10 \text{ Gauss}$$

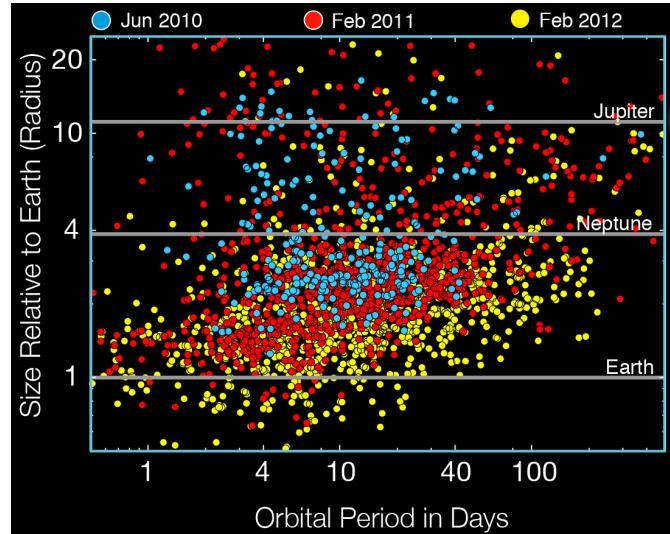
$$H \sim 0.02 a \sim R_{\text{roche}}$$

Super Earths: some key issues

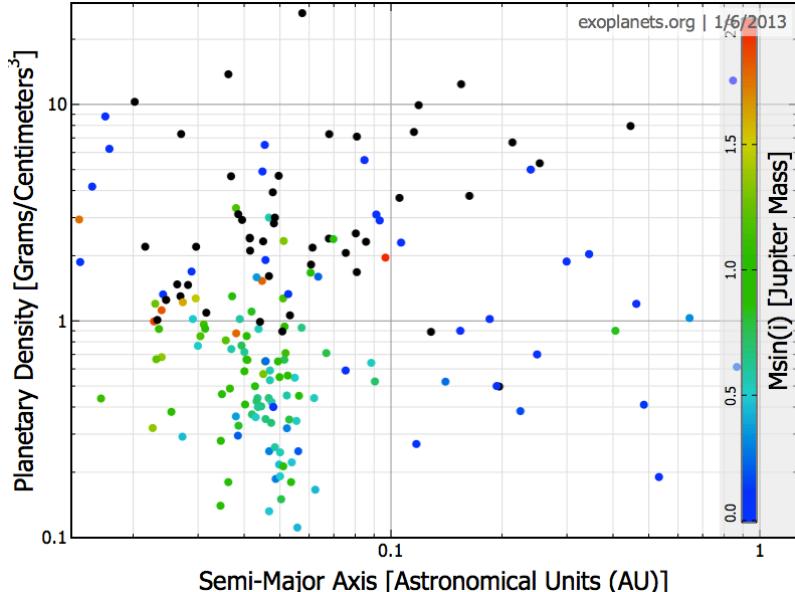
- What determines the period distribution?



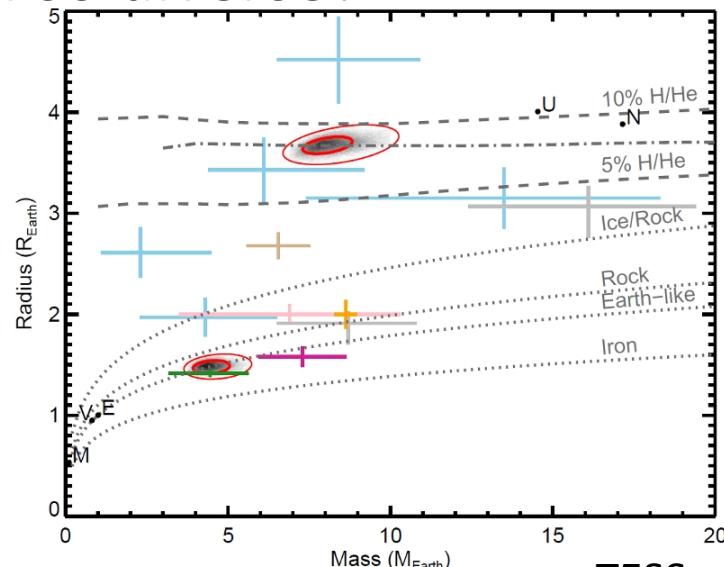
Does the M-P distribution fall off?



- Why is density-period distribution so diverse?



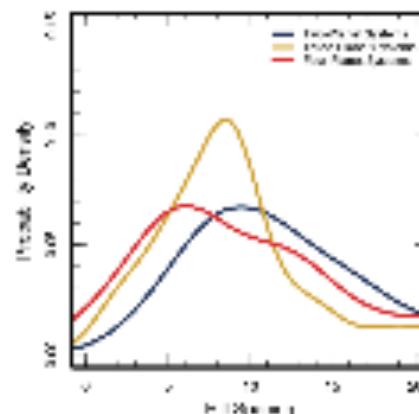
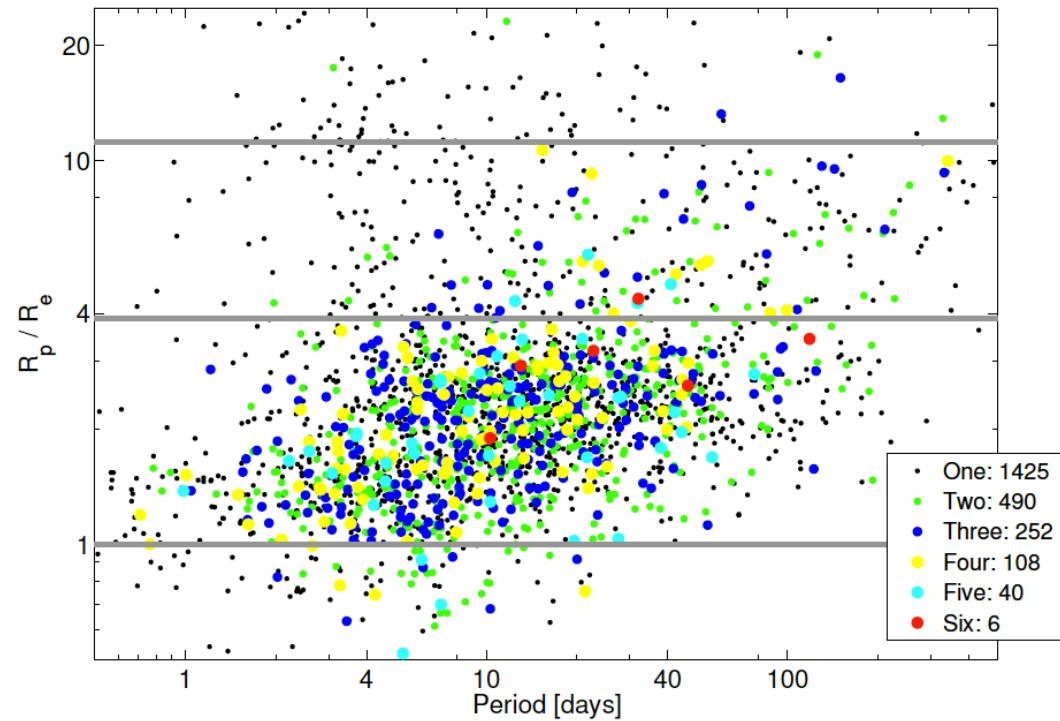
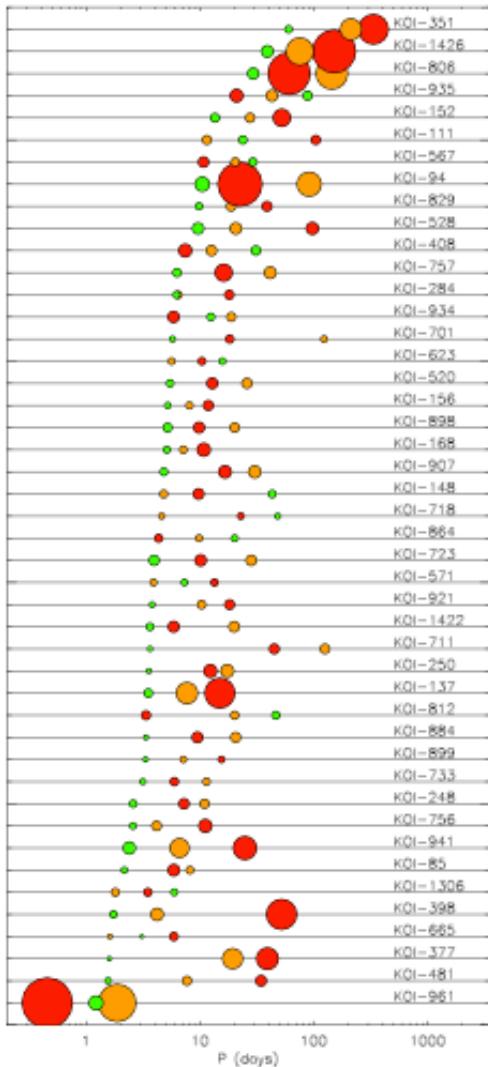
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TESS

New Candidate Catalog (Batalha et al. 2012)

What can we learn from Multiple systems !!!

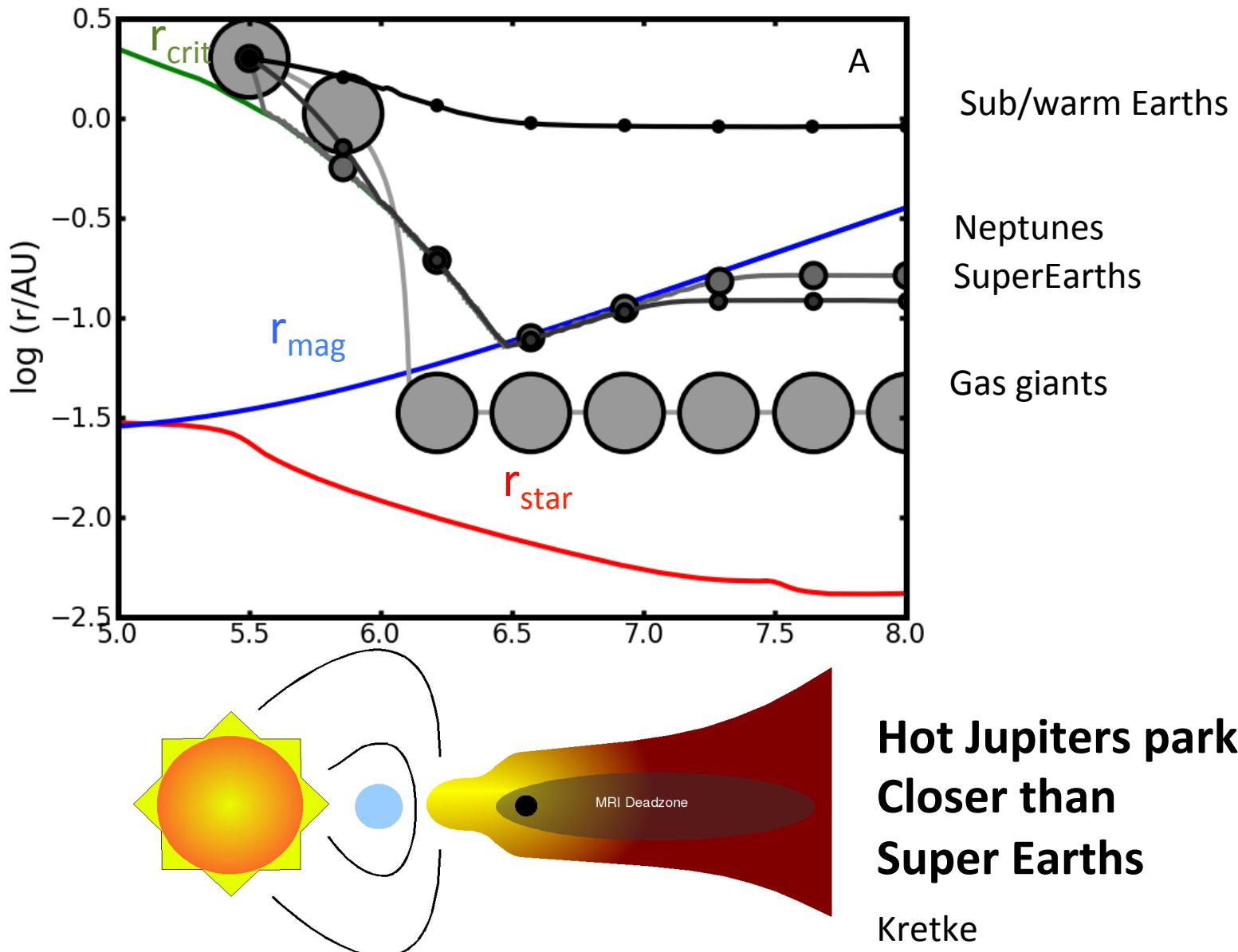


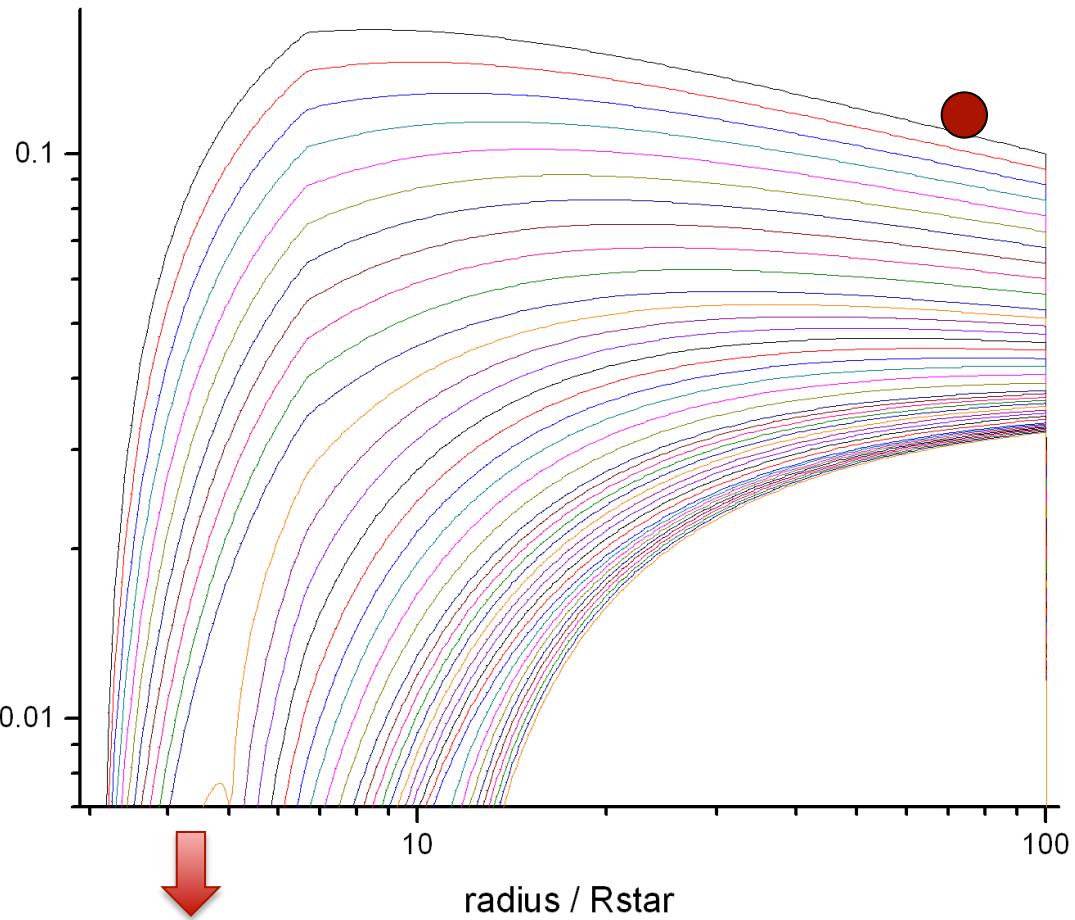
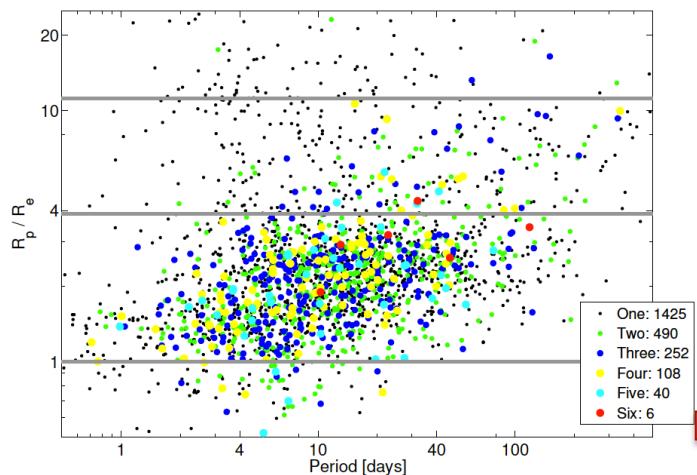
How compact can
multiple systems be?

Kevin Schlaufman
Xiaochen Zheng

Super Earths: some key issues

- How to differentiate type I and II migration?





Migration of a Super Earth in protostellar disk around a magnetized T Tauri star. The Super Earth: (a) grows & migrate inward to inner-edge; (b) migrates slightly outwards with the expanding disk inner edge; (c) halts migrating after gas is mostly depleted. (Ju et al 2012 in preparation)



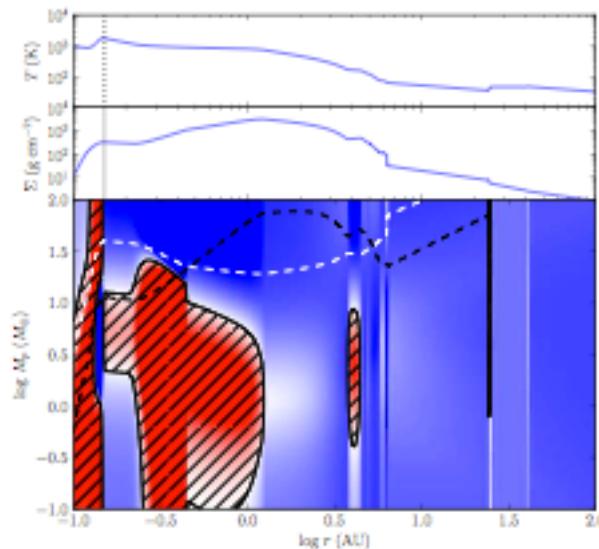
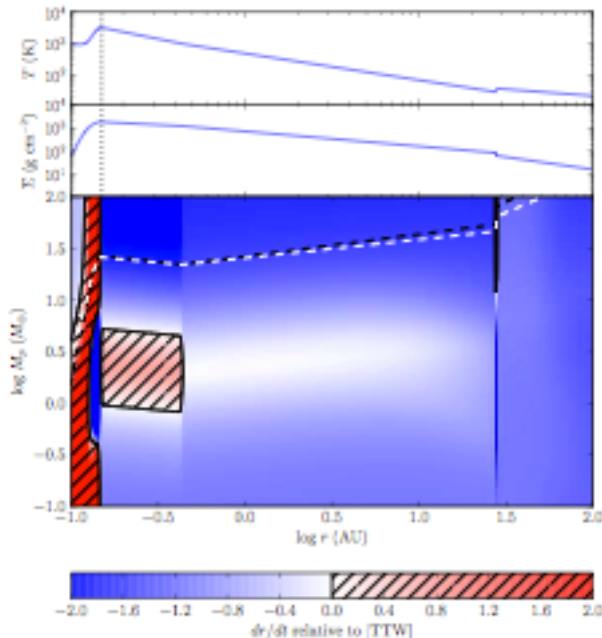
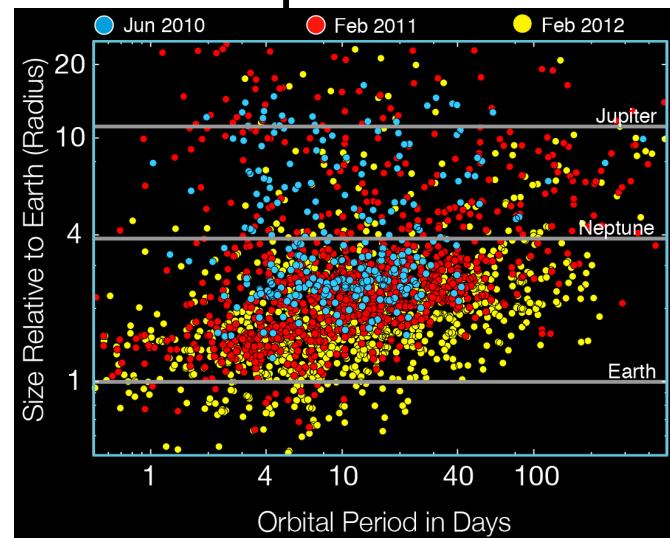
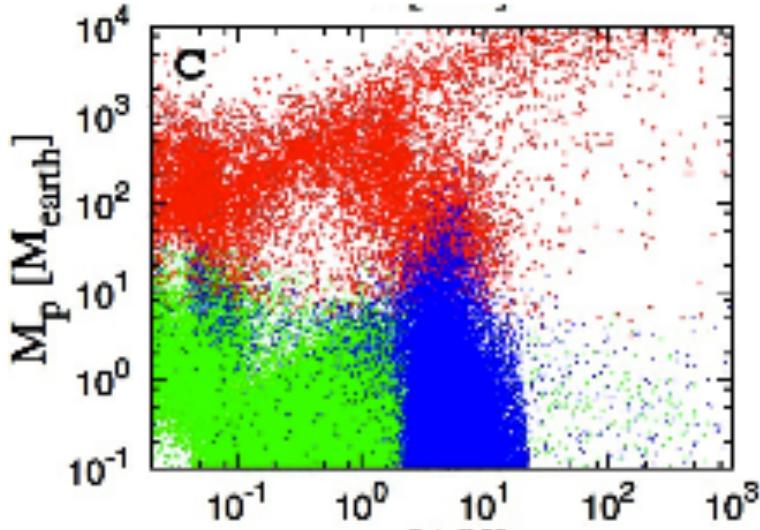
To model P distribution
of Kepler's new-found
planetary candidates.



KIAA undergraduate
student Ju Wenhua
now at Princeton U

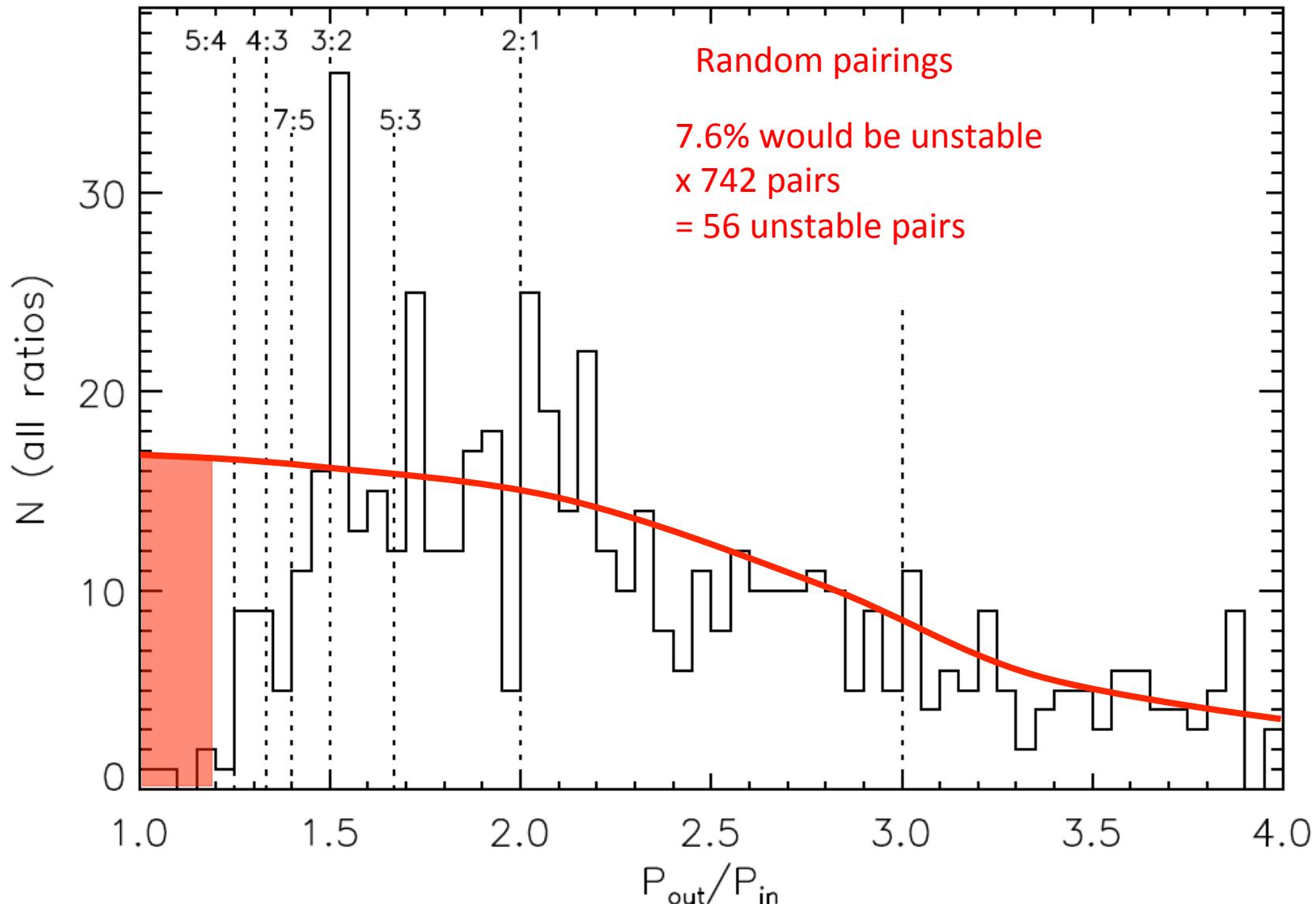
Super Earths: some key issues

- What determines the super-Earths' mass-period domain?

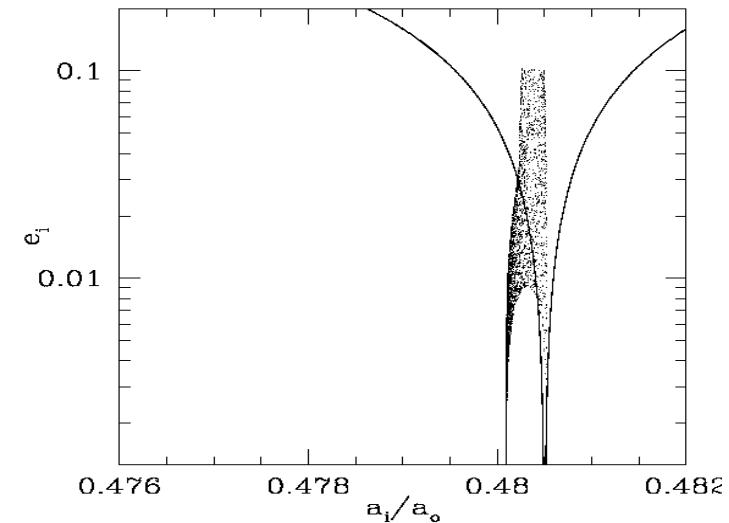
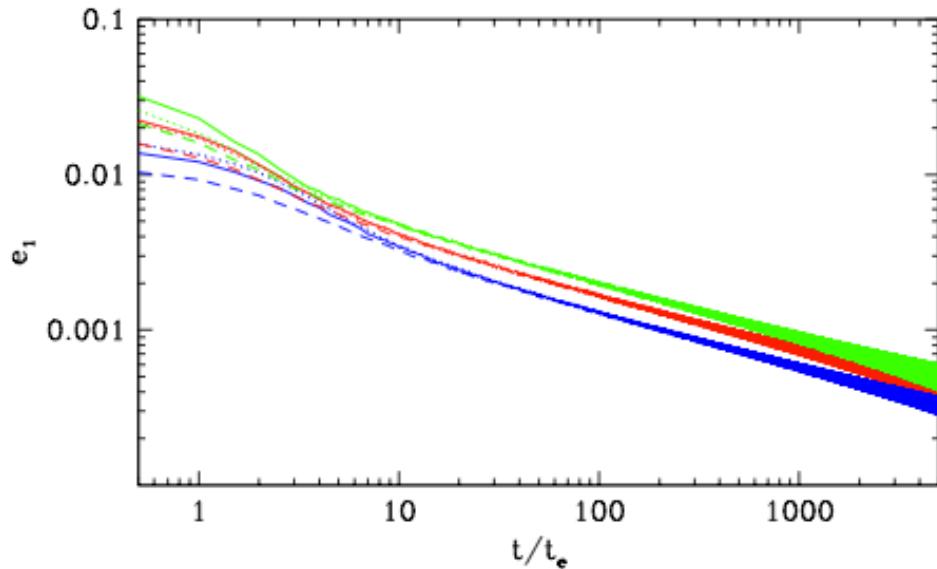


Super Earths: some key issues

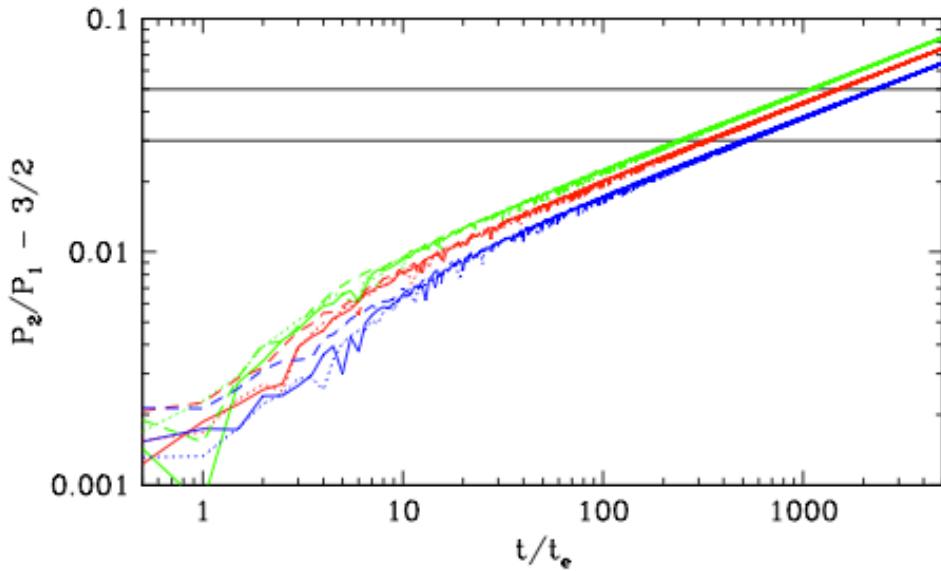
- Did planets capture each other and parted their ways?



Resonance breaking

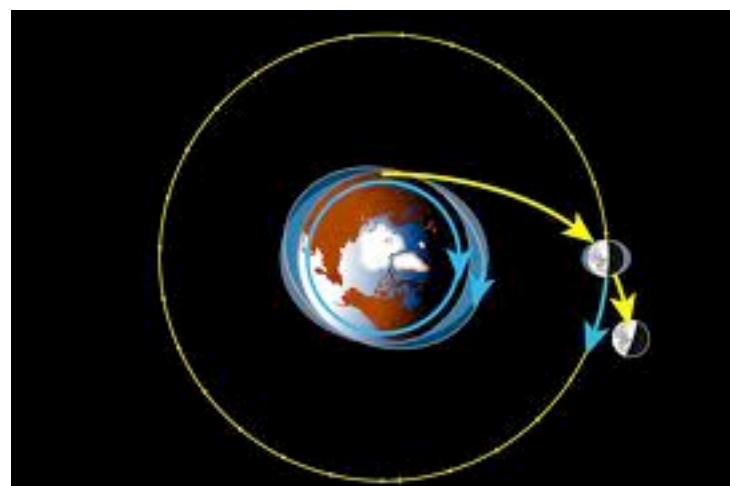
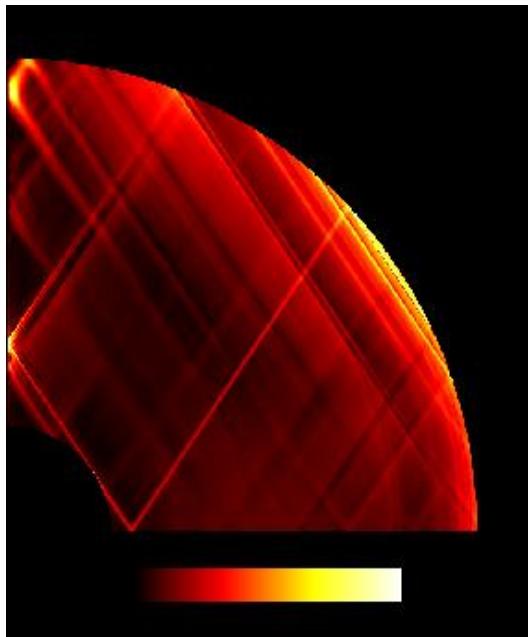
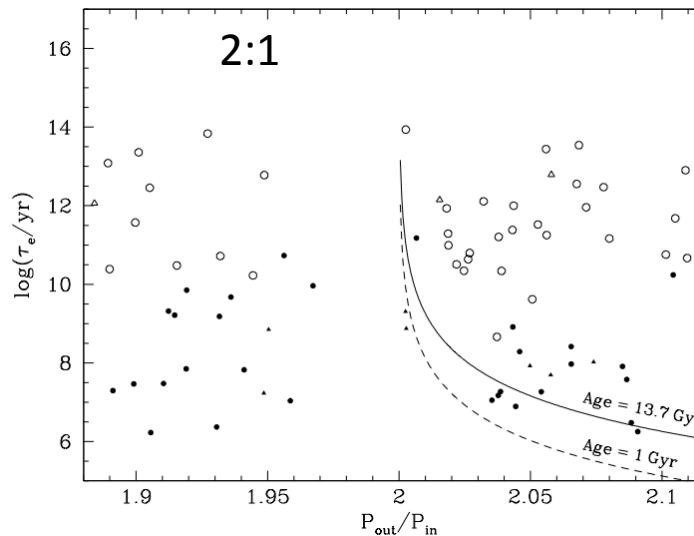
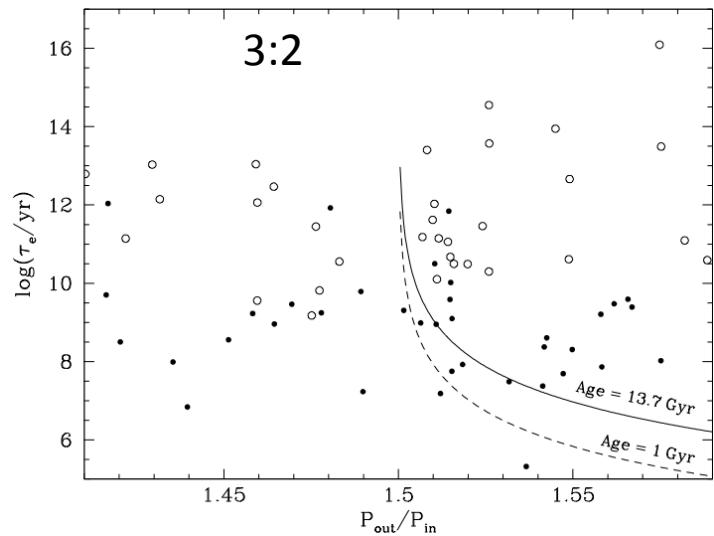


Novak, Lai



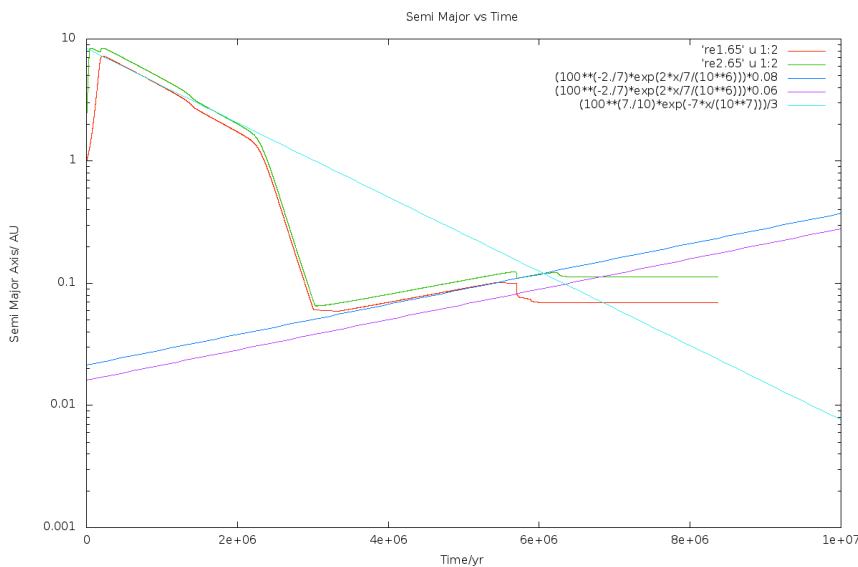
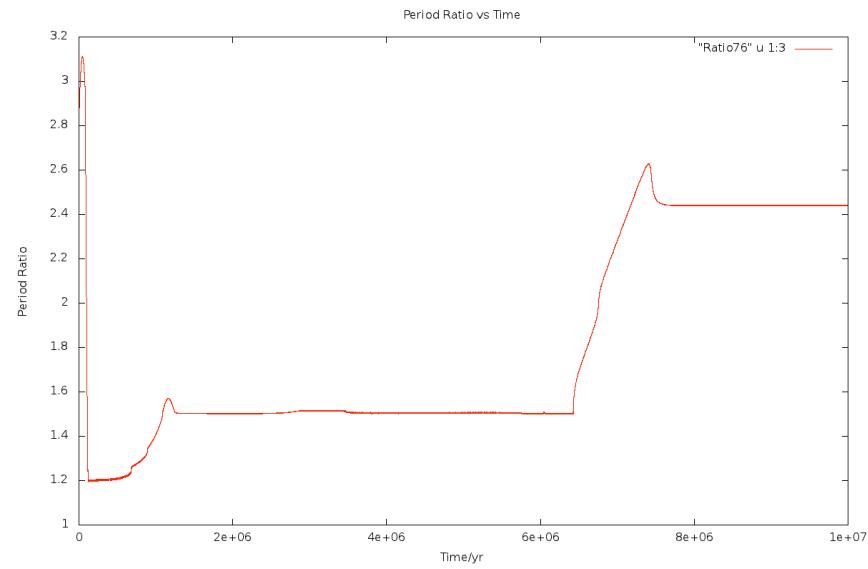
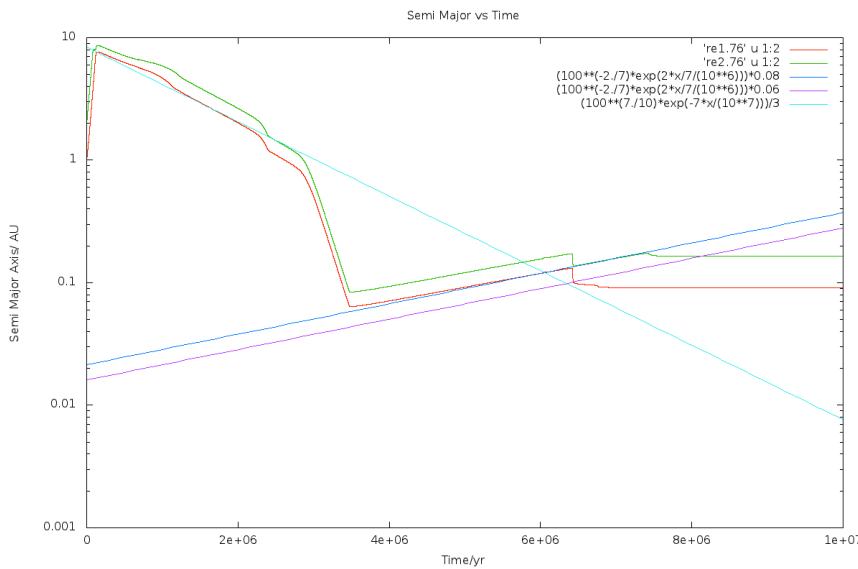
Super Earths: some key issues

- Can tidal dissipation really cause orbital evolution at large a ?

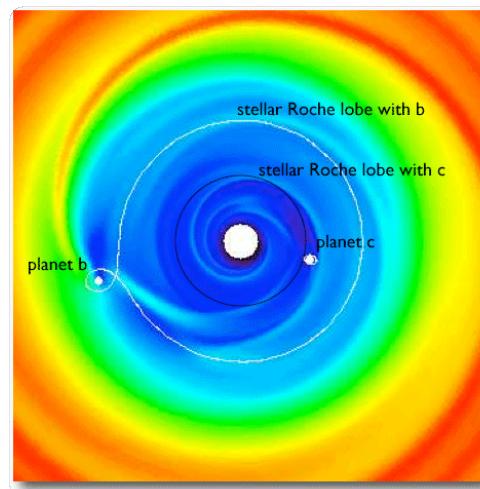


Super Earths: some key issues

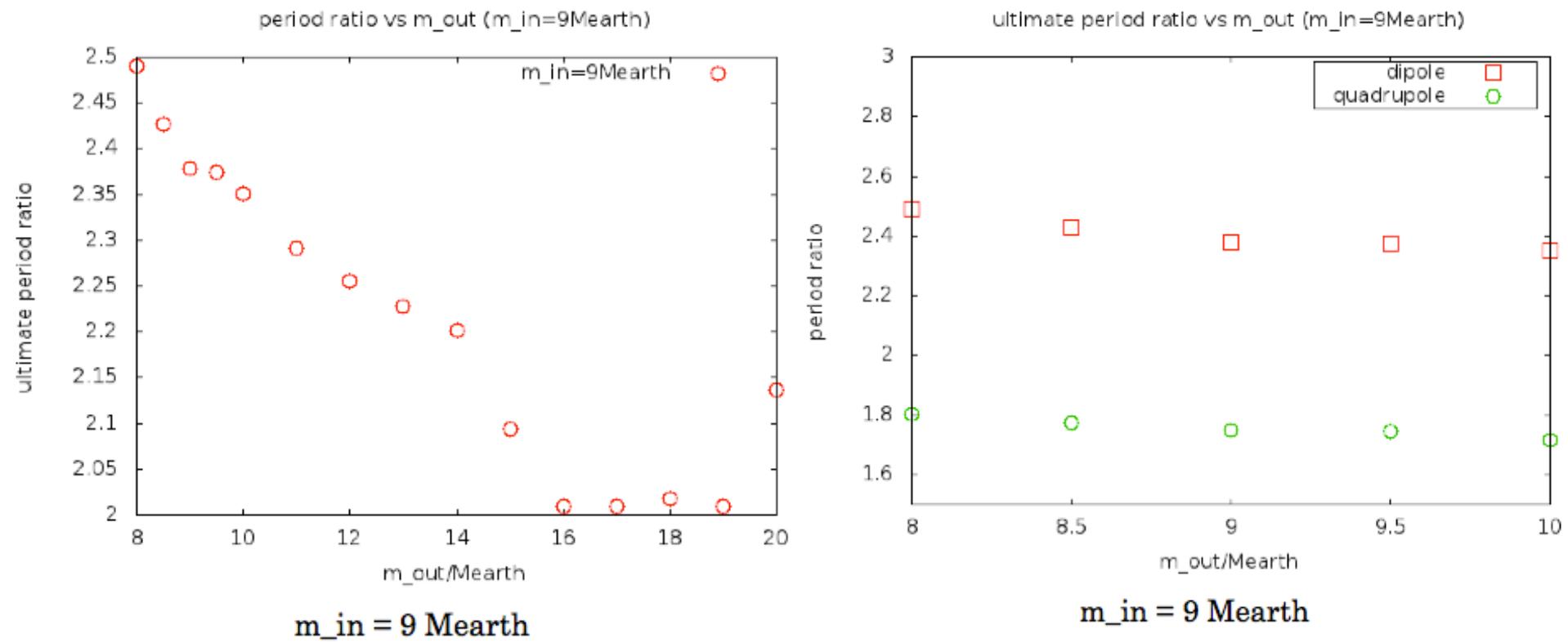
- Can type I migration be resurrected at the late stages?



Bin Dai

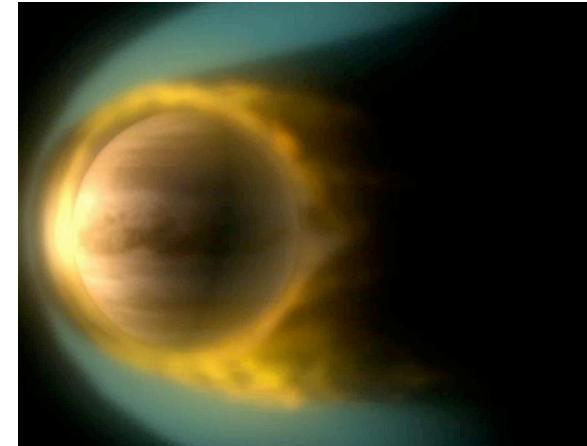
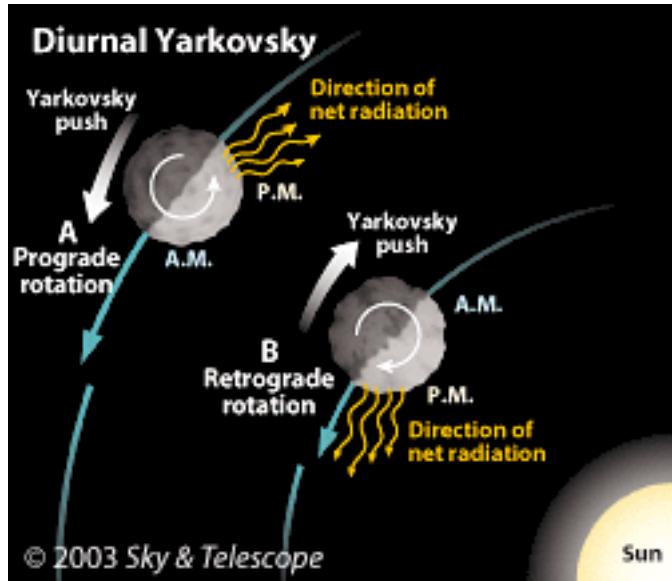


Asymptotic period ratio



Super Earths: some key issues

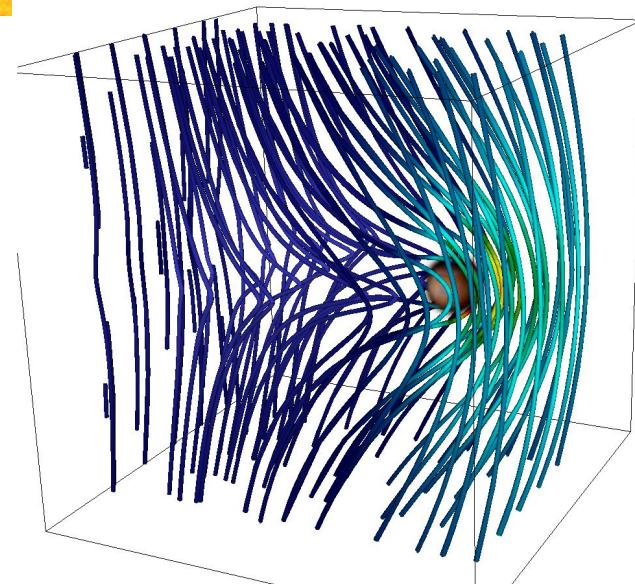
Are there many diverse migration mechanisms



Wei Zhu

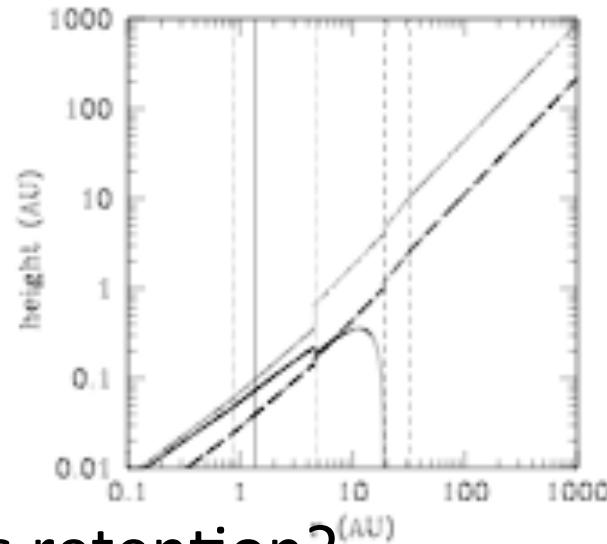
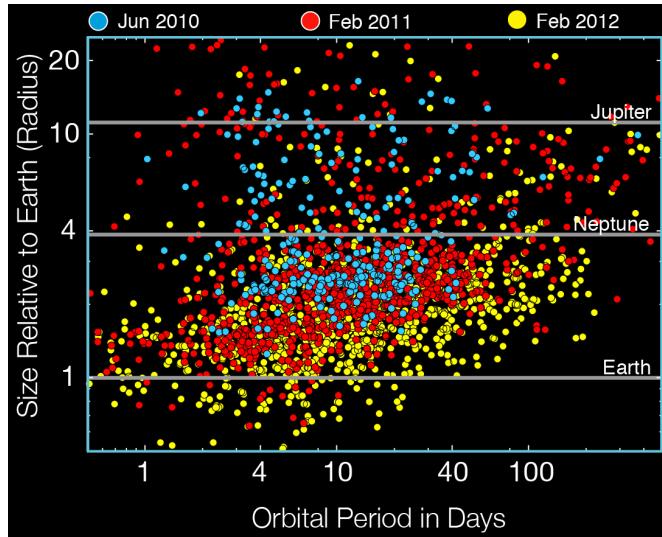
$$\tau_a = 4 \times 10^8 \text{ yr} \left(\frac{\rho_p}{1 \text{ g/cm}^3} \right) \left(\frac{r_p}{1 \text{ km}} \right) \left(\frac{a}{1 \text{ AU}} \right)^{3/2} (1-e^2)^{1/2}$$

Resonant capture
Collisional damping
Gas drag

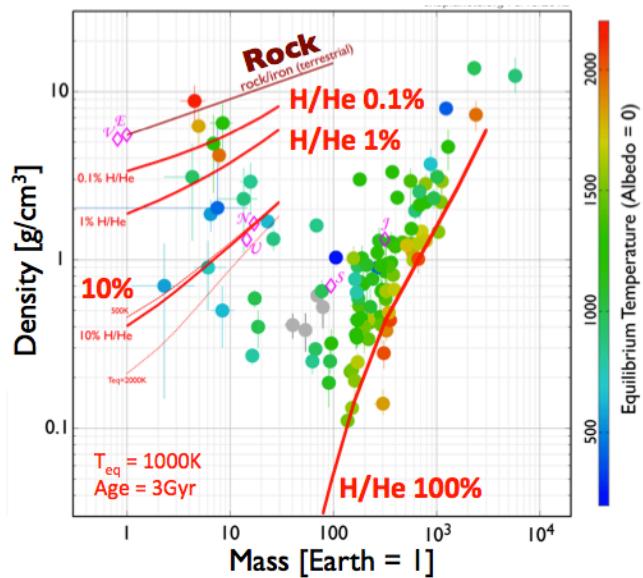


Super Earths: some key issues

- How to suppress gas accretion onto super-Earth?



- Is there a critical condition for gas retention?



Ikoma

Other issues

Late-stage evolution in debris disks

Post formation dynamical evolution

Non planar planetary systems

Planets around different mass stars

The role of elemental differentiation in natal disks

Planets in binary stars

Planets around stars in clusters

Planets' magnetic and tidal interaction with their host stars

Planets' consumption by their host stars

Planets' survival around evolved stars

Planets' internal structural evolution

Planets' atmospheric dynamics

How is habitability affected by dynamical interaction between planets

Summary

- Theory is an useful exercise for the interpretation of data and planning of exploration strategy.
- Planetary astrophysics is a rich discipline which can be tackle at all levels.
- Planet formation is a robust process and their dynamical architecture is diverse.
- Migration played a big role in their final destiny.
- Theory of planetary astrophysics is relevant to many other astrophysical contexts.